Boiler Drum Water Level Control based on Linear Active Disturbance Rejection and Gray Correlation Compensation

Di Wang, Haoyu Li, Xinyan Xie, Deying Liu

Northeast Electric Power University, School of Automation Engineering, China
(e-mail: wd1989125@163.com, Corresponding author: 894522476@qq.com,
1834152275@qq.com, 408537099@qq.com).

Abstract: Boiler drum water level stability is an important foundation for the safe and stable operation of thermal power plant. However, drum water level is often interfered by the steam and feed water flow rate, which brings a lot of problems to boiler drum water level control. In this work, a novel controller base on the linear active disturbance rejection controller (LADRC) and gray correlation compensation (GCC) is proposed to maintain the drum water level. The compensation coefficient of GCC is calculated by the output of linear extended state observer (LESO). The simulation results indicate the LADRC-GCC controller can maintain a more stable drum water level than LADRC or non-linear active disturbance rejection controller (NLADRC). Moreover, the LADRC-GCC controller can compensate for different disturbances in time for drum water level. The control method proposed provides the reference for the drum water level control optimization.

Keywords: drum water level; compensation control; linear active disturbance rejection controller (LADRC); gray correlation calculation (GCC)

1. INTRODUCTION

Thermal power plant has always played an important role in the electric power generation enterprise. More than 70% of the China's electricity is generated by coal-fired power plants (Wang, 2016).

For the natural circulation boiler of coal-fired power plant, the excessive drum water level can damage the normal operation of the separation device seriously, and even cause the steam mingling with water. And if the drum water level is too low, the boiler water circulation will be destroyed and cause the collapse of water wall. In addition, once feed water flow rate fluctuates, it has negative influence on the safety operation of the coal-fired power plant.

With the increase of electricity consumption in China, electricity equipment puts forward higher requirements for the power quality (Wang et al., 2015). And as the power load frequency increasing, the coal-fired power plant load change rate needs to speed up. Boiler feed water flow rate and the ability to follow the command need to be improved as well (Pan et al., 2015).

Many research results on the boiler drum water level control have been achieved (Mello and Fellow, 1991; Åström and Bell, 2000; Chaibakhsh and Ghaffari, 2008; Tunckaya and Koklukaya, 2015; Buczyński et al., 2015; Oko et al.,2015). Moradi et al. applied the sliding mode control and H_∞-robust to steam drum water level control (Moradi et al., 2012). Sunil et al. improved the performance of boiler drum water level control by using the quantitative feedback theory (QFT) method (Sunil et al., 2020). Xu et al. proposed a cascade model predictive control scheme for boiler drum water level (Xu et al., 2005). Wu et al. designed the model predictive controller and applied it to the drum water level (Wu et al., 2014). Liu et al. designed the DMC-PID cascade control system for drum water level (Liu et al., 2004). Yue and Liu applied the adaptive fuzzy-PID controller to the drum water level (Yue and Liu, 2009). Chandrasekharan et al. discussed the application of different multivariable-control strategies to the boiler drum water level (Chandrasekharan et al., 2018). Zhou et al. designed a new immune PID controller and applied it to the drum water level (Zhou and Sun, 2011). Yu et al. researched the adaptive gray prediction algorithm and applied it to the drum water level (Yu et al., 2006). Gandhi and Adhyaru optimized the boiler drum water level control using the separation principle (Gandhi and Adhyaru, 2013).

In the above research results, many theoretical foundations are provided for the control of drum water level. However, most of the above control algorithms has the complicated structure, is difficulty to be used in the field.

Active disturbance rejection controller (ADRC) is easy to be achieved in the actual process. ADRC has been applied in different fields. It should be mentioned that ADRC does not depend on the accurate model. Guan applied ADRC technology to the coal mill outlet temperature control of thermal power plant (Guan, 2009). Wu et al. proposed a gain scheduling design based on ADRC for thermal power plants under full operating conditions (Wu et al., 2019). In order to improve the control quality of the thermal power main steam temperature control system in the process of the unit participating in the deep peak shaving, Han et al. proposed a fuzzy ADRC cascade control scheme (Han et al., 2018). Huang et al. designed the ADRC that can be used for subway train braking and verified its feasibility (Huang et al., 2019).

Shen et al. proposed the controller based on ADRC technology to solve the control problem of autonomous underwater vehicle (Shen et al., 2016). The control strategy based on ADRC was established in turboprop aircraft (Sheng et al., 2018). To solve the tension disturbance problem of the strip processing line due to the motion of the looper carriage, Zhang et al. presented an ADRC strategy (Zhang et al., 2018). Najm et al. proposed an ADRC to the stabilize and reject exogenous disturbances and system uncertainties for a 6-degree of freedom quadrotor system (Najm et al., 2020). The ADRC was proposed as the control strategy for anti-lock braking system to improve the braking performance (Li et al., 2020). Zhang et al. investigated the control strategy that combines generalized ADRC and Smith predictor (Zhang et al., 2020).

In addition, ADRC has strong robustness, which can ensure the stability of controlled system when the model is not precise. Li proposed a novel control method which is fuzzy immune linear active disturbance rejection control (LADRC) technology (Li et al., 2015). In order to solve the problem of excessively high bypass temperature in the FCB process, the control technology based on static the feed-forward and LADRC was proposed (Zhou et al., 2017).

However, with the improvement of the precision requirement of control parameters in industrial process, some shortcomings are exposed in ADRC. With the frequency increment of grid load changes, the main steam pressure, boiler main steam and feed water flow rate of coal-fired power plant will change frequently, which leads to fluctuations of boiler drum water level.

In order to solve above problem, the LADRC combined with gray correlation compensation (GCC) is proposed in this work. Since the gray correlation compensation of GCC cannot be determined, this study applies the observation error of the expanded state observer (ESO) to determine the gray correlation compensation of GCC, the results show that LADRC-GCC can adaptively adjust the compensation coefficient with the disturbance.

2. LINEAR ACTIVE DISTURBANCE REJECTION CONTROL

Aiming at the shortcomings of PID controller, Han proposed active disturbance rejection control, which is composed of three parts: tracking differentiator (TD), ESO, and the non-linear state error feedback (NLSEF) (Han, 1995; 1998; 2002; 2007).

However, due to the difficulties in adjusting so many parameters, its application in engineering is limited. Gao proposed the linear active disturbance rejection control by linearization techniques of three parts of ADRC and obtained good control effect (Gao, 2003).

The idea of LADRC is based on the theory of ADRC, but there are obvious differences between the two controllers.

(1) ADRC involves TD to enable the tracking signal inputs v_1 and differential form v_2. In LADRC, assuming LADRC observation is accurate, then v_1, v_2 can be estimated directly from LESO, its structure is simpler and easier to implement.

(2) The ESO is transformed from the original third order nonlinear form into the multi-order state space realization form, which improves the accuracy and the bandwidth.

(3) NLSEF law is used in ADRC and linear control law is applied in LADRC, the LADRC is easier to achieve in practice than NLSEF.

In general, a second-order system can be expressed as follows (Gao, 2003):

$$\ddot{y} = -a_1\dot{y} - a_2 y + w + bu \tag{1}$$

where, u is the input of system, y is the output of system, w is the disturbance of system, a_1, a_2 are the system parameters, b is the control gain (Gao, 2003; Han, 2009).

Setting $x_1 = y$, $x_2 = \dot{y}$ and $f(y, \dot{y}, w) = -a_1\dot{y} - a_2 y + w + (b - b_0)u$ as the generalized disturbance of system, then the disturbance contains the external and internal disturbance, the form of state variables of the system is $x_3 = f(y, \dot{y}, w)$, equations of state Eq. (1) can be obtained as Eq. (2) (Gao, 2003; Han, 2009).

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + b_0 u \\ \dot{x}_3 = h \\ y = x_1 \end{cases} \tag{2}$$

where, x_1, x_2, x_3 are the state variables of the system, b_0 is the estimation of b, $h = \dot{f}(y, \dot{y}, w)$.

2.1 Linear extended state observer (LESO)

The linear state observer (LESO) of the LADRC is established as:

$$\begin{cases} \dot{z}_1 = z_2 - \beta_1(z_1 - y) \\ \dot{z}_2 = z_3 - \beta_2(z_1 - y) + b_0 u \\ \dot{z}_3 = -\beta_3(z_1 - y) \end{cases} \tag{3}$$

Selecting the appropriate observer gain β_1, β_2, β_3, LESO is able to achieve the tracking of the system, $z_1 \to y$, $z_2 \to \dot{y}$, $z_3 \to f(y, \dot{y}, w)$.

Setting $u = \dfrac{-z_3 + u_0}{b_0}$, and ignoring the estimation error of Z_3, the system can be simplified as a double integral series structure as Eq. (4).

$$\ddot{y} = (f(y, \dot{y}, w) - z_3) + u_0 \approx u_0 \tag{4}$$

2.2 PD controller

The PD controller is built up as:

$$u_0 = k_p(v - z_1) - k_d z_2 \tag{5}$$

where, v is the setting signal; c_{ap}, k_{ed} are the controller parameters.

The closed-loop transfer function is

$$G_{c1}(s) = \frac{k_p}{s^2 + k_d s + k_p} \tag{6}$$

The Eq. (6) can be obtained based on Eq. (4) and Eq. (5), selecting the appropriate gain y_d, c_{ap}, the system can be stable. The LADRC of the Eq. (1) is established, the structure is shown as Fig. 1, the G(s) is the controlled model, which is the model between the feed water flow rate and the drum water level in this work.

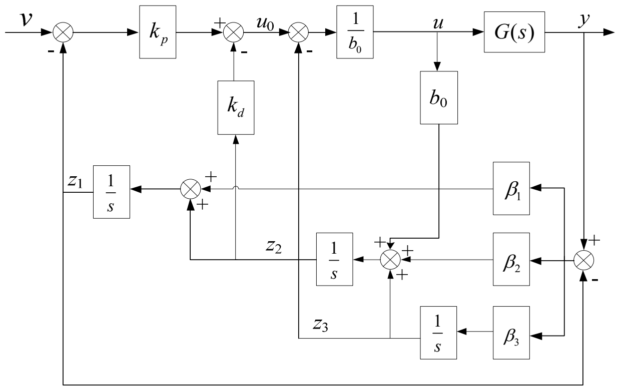

Fig. 1. Structure of LADRC.

The characteristic equation of LESO is obtained as Eq. (7).

$$\lambda(s) = s^3 + \beta_1 s^2 + \beta_2 s + \beta_3 \tag{7}$$

Selecting $\lambda(s) = (s+\omega)^3$ as the ideal characteristic equation, then $\beta_1 = 3\omega_0$, $\beta_2 = 3\omega_0^2$, $\beta_3 = \omega_0^3$, ω_0 is observer bandwidth, selecting parameters of Eq. (6) as $k_p = \omega_c^2$, $k_d = 2\xi\omega_c$, a_{ct} is controller bandwidth, ξ is the damping ratio, sets ξ=1 in this paper, then the characteristic equation is $\lambda(s) = (s+\omega)^2$ based on Eq. (6).

3. GRAY CORRELATION COMPENSATION

The gay system theory was built in 1982 by Chinese scholar Professor Deng, which refers to incomplete information system that means the information factors and system structures are not completely clear (Deng, 1982). In recent years, the gray system theory has been used in the field of economic management (Jia et al., 2015), social systems (Tan et al., 2014), ecosystems (Qin et al., 2006), and so on.

The gray system theory includes gray relation, gray prediction, gray decision and modelling, where gray relation is gray correlation analysis (GCA), which is a novel kind of statistical analysis. It investigates correlation among factors on the development trend of things by comparison. In fact, it is a kind of comparative analysis of sequences and their curves which means the closer and more similar the sequences or curves are in general, the greater the relevance of the overall case will be.

A method is proposed to calculate the weight of gray correlation for drum water level control in this work. Calculation process is as follows:

(1) Supposing at time t, the first n samples of input and output time steps are $\{y(t-n+1), y(t-n+2), \ldots, y(t)\}$, $\{r(t-n+1), r(t-n+2), \ldots, r(t)\}$ respectively.

(2) According to the gray correlation proposed, when the drum water level control system output and input values get closer, the higher the similarity between them is, the greater the grey correlation degree is, which makes the compensation inputs smaller.

(3) The lower similarity of two sequences is, and the larger compensation inputs should be. That is, input and output sequence of the gray correlation is calculated with an inverse proportional relationship to the compensation input.

(4) Meanwhile, positive or negative values of the compensation have relationship with the input and output. When the given input is greater than the output, the compensation input should be a negative value, which on the contrary should be positive.

(5) When the given input is equal to the output, the compensation input is 0.

The gray correlation needs to meet the following four axioms (Deng, 1982; Jia et al. 2015):

(1) Normalization:

$$0 < \gamma(X_0, X_i) \le 1 \tag{8}$$

$$\gamma(X_0, X_i) = 1 \Leftrightarrow X_0 = X_i \tag{9}$$

(2) Integrity:

For $X_i, X_j \in X = \{X_s \mid s = 0,1,2,\cdots,m; m \ge 2\}$,

$$\gamma(X_i, X_j) \ne \gamma(X_j, X_i) \tag{10}$$

Where, $i \ne j$.

(3) Symmetry:

For $X_i, X_j \in X$,

$$\gamma(X_i, X_j) = \gamma(X_j, X_i) \Leftrightarrow X = \{X_i, X_j\} \tag{11}$$

(4) Proximity:

If $|x_0(k) - x_i(k)|$ is smaller, $\gamma(x_0(k), x_i(k))$ is greater.

Where, $X_0 = (x_0(1), x_0(2), \cdots, x_0(n))$ is a system reference sequence, $x_0(k)$ is the k-th data of X_0, $x_i(k)$ is the k-th data of X_i, X_i and X_j are the related sequences, k represents the k-th data, $\gamma(X_0(k), X_i(k))$ is the gray correlation coefficient of X_i and X_0.

The compensation control law of GCC proposed in this work is shown as Eq. (12).

$$u_c = K\left\{\frac{1}{n}\sum_{k=1}^{n}\frac{B}{A+B}\right\}^{-1} sign(r-y) \quad (12)$$

Where,

$$A=\lambda_1\left|r(k)-y(k)\right|+\lambda_2\left|r'(k)-y'(k)\right|$$

$$B=\varepsilon \max_{k\in[1,n]}\left|r(k)-y(k)\right|$$

$$r'(k)=\begin{cases} r(k) & k=1 \\ r(k)-r(k-1) & k=2,3,\cdots,n \end{cases}$$

$$y'(k)=\begin{cases} y(k) & k=1 \\ y(k)-y(k-1) & k=2,3,\cdots,n \end{cases}$$

r is ideal output, y is actual output, u_c is the gray correlation compensation, K is the gray correlation compensation coefficient, ε is constant, λ_1 is error weighting factor, λ_2 is rate weighting factor.

The compensation coefficient of GCC cannot be determined, and has great influence on the controller performance. When the compensation coefficient is fixed, the compensation ability is limited with the change of external disturbance.

A method of adaptive change of GCC compensation coefficient is proposed. The compensation coefficient is determined by the observation error of the LESO output. When the observation error is large, the compensation coefficient increases. When the observation error is small, the compensation coefficient decreases.

According to the above idea, this work puts forward the adaptive change rule of compensation coefficient, is shown as Eq. (13):

$$K=\psi f(e_1) \quad (13)$$

Where, $f(x)=|x|$, ψ is the coefficient of GCC intensity, and $e_1=z_1-y$.

4. SIMULATION TEST

4.1 Drum water level model

As a crucial parameter, the stability of drum water level is a necessary condition for maintaining the operation of steam turbine and boiler. The boiler drum structure and is shown as Fig. 2, the n_D is the coefficient of steam flow rate measuring device, n_G is the coefficient of feed water flow rate measuring device, γ_D, γ_H, and γ_G, are constants.

The excessive drum water level will affect the normal operation of the water separator. Meanwhile, it will make the superheater tube wall scale and the superheater steam temperature change dramatically, which will affect the safety and economy of the plant operation.

If the drum water level is too low, it could damage the water circulation and burn out the water wall of the boiler.

Boiler drum is an important device for steam and water separation which contains steam and vapour-water mixture. In the drum, the fluid above and below the water level are saturated steam and vapour-water mixture. The fluids at the outlet of riser is vapour-water mixture, unsaturated boiler feed water W enters the drum from economizer, and leaves in the form of saturated steam D, meanwhile, drum water level is controlled by regulating the feed water flow rate.

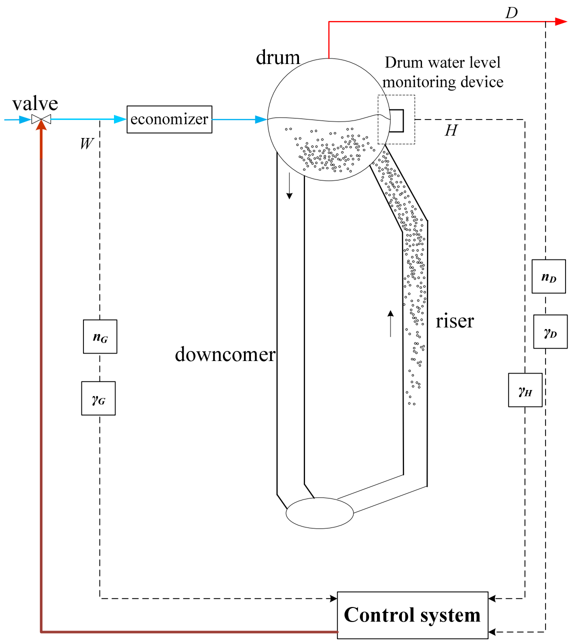

Fig. 2. Structure of boiler drum-downcomer-riser system.

The disturbance of drum water level is divided into the external and internal disturbance. The external disturbance is mainly the changes of steam flow rate at the outlet of drum, and the internal disturbance is mainly the feed water flow rate changes. In general, the boiler drum water level control structure is shown as Fig. 3, where, the controller $G_c(s)$ is the P controller, $G_m(s)$ is the PI controller generally.

Since this work mainly studies the boiler drum water level control method, the establishment of the mathematical model of drum water level is not the focus. The model used in this research is obtained from the field operation data, and mainly used for the controller design (Liu et al., 2004).

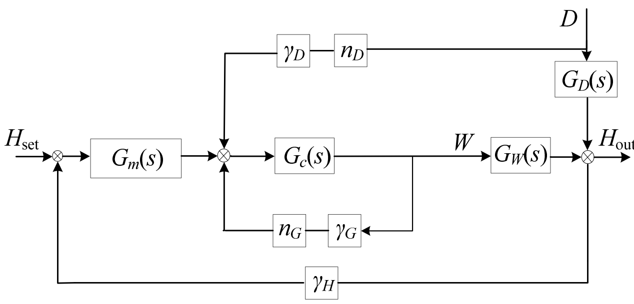

Fig. 3. Boiler drum water level traditional control system

The controlled model of the drum water level is shown as Eq. (14) and Eq. (15), $G_W(s)$ is the model between feed water flow rate and drum water level, and the $G_D(s)$ is the model between steam flow rate and drum water level. The model parameters are shown in Table 1 (Liu et al., 2004).

$$G_W(s) = \frac{H(s)}{W(s)} = \frac{\theta}{s(T_1 s+1)} \tag{14}$$

$$G_D(s) = \frac{H(s)}{D(s)} = \frac{K_d}{T_2 s+1} - \frac{\theta}{s} \tag{15}$$

Table 1. Model parameters

Parameters	unit	Value
K_d	-	3.6
θ	-	0.037
T_1	s	30
T_2	s	15
n_D	-	0.21
n_G	-	0.21
γ_D	-	0.083
γ_G	-	0.083
γ_H	-	0.033

The LADRC-GCC controller is used in this work, and the control system structure is shown as Fig. 4. The GCC parameters are shown as Table 2, and the LADRC parameters are shown as Table 3 (Zhou et al., 2017).

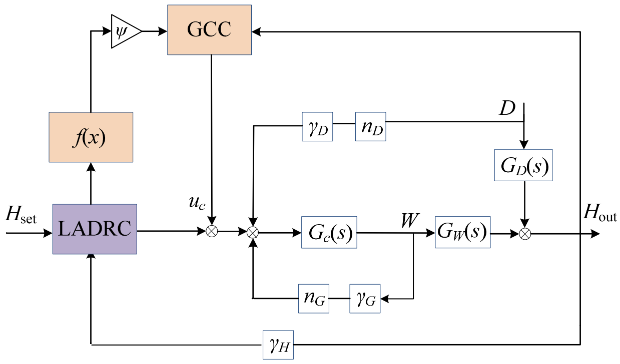

Fig. 4. Control system based on LADRC-GCC.

Table 2. GCC parameters

Parameters	Value
ψ	10
ε	0.5
λ_1	0.9
λ_2	0.1

Table 3. LADRC parameters.

Parameters	Value
ω_0	1.05
ω_c	10.2
b_0	0.002

4.2 Steam flow rate disturbance

As the external disturbance, steam flow rate influences drum water level directly, however, main steam pressure and other parameters of thermal power plant lead the changes of main steam flow rate as well. In order to study the control performance of LADRC-GCC for the external disturbance, simulation test of main steam flow rate step changes 10% is carried out. The simulation test is carried out on the MATLAB / Simulink R2014a platform, the sampling step of gray correlation algorithm is 0.01s, and the Runge-Kutta algorithm is used to solve the model, in which the sample time is 0.01s .

To compare with other controllers, the LADRC and non-linear active disturbance rejection controller (NLADRC) are built up, the parameters setting of NLADRC are based on the principle in reference (Han et al. 2008), parameters of LADRC are the same with LADRC-GCC.

The simulation results are shown as Fig. 5. Three controllers can control the water level to reach the set value. However, the regulation time of NLADRC and LADRC-GCC is about 7.5s, and that of LADRC is about 30s. Moreover, the overshoot of LADRC is the largest, and that of LADRC-GCC is the smallest.

Therefore, from the analysis of overshoot and regulation time, the rapidity and stability of LADRC-GCC is the best among the three controllers.

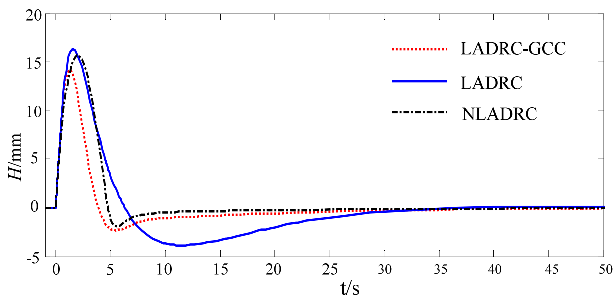

Fig. 5. Drum water level characteristic under the step disturbance of main steam flow rate.

Dynamic characteristic of the compensation coefficient of GCC under the main steam flow rate step disturbance is shown as Fig. 6.

When the steam flow rate at the outlet of the drum occurs step disturbance, K increases rapidly. As the drum water level is stable, K tends to be 0, the feed water flow rate tends to be

2stable, which can change adaptively with the drum water level change.

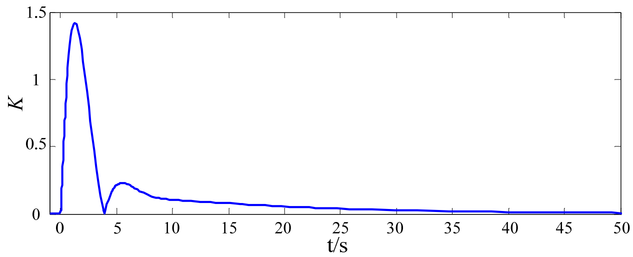

Fig. 6. K changes under the step disturbance of main steam flow rate.

Outputs of LESO of LADRC-GCC under the step disturbance of main steam flow rate are shown as Fig. 7.

The LESO of LADRC-GCC can track the position of variables relatively accurately, based on the observation results of LESO and Eq. (12), the feed water flow rate regulation instruction can be obtained.

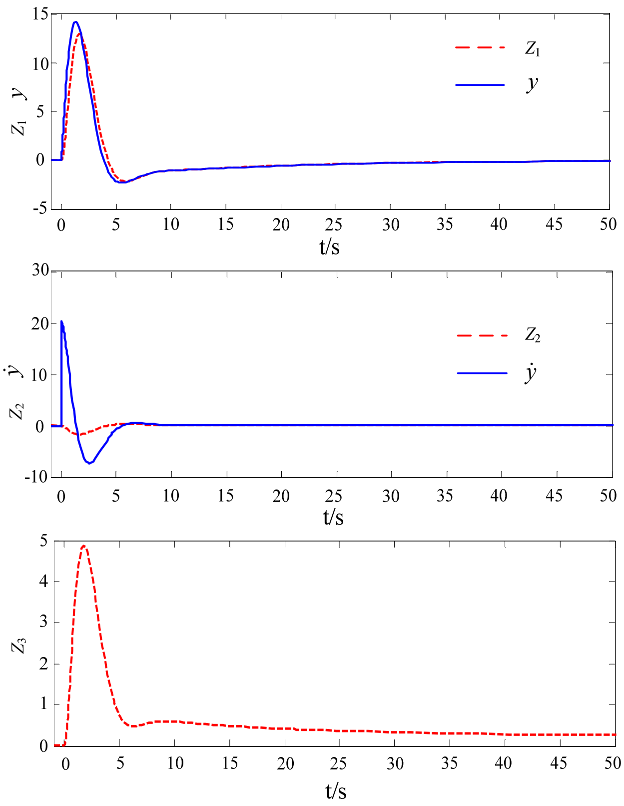

Fig. 7. LESO outputs under the step disturbance of main steam flow rate.

In order to discuss the effect of the gray correlation compensation intensity coefficient, the simulation tests of main steam flow rate step disturbance under different coefficient of GCC intensity are carried out, and the results are shown as Fig. 8.

With the increase of ψ, the regulation time and overshoot are reduced, however, the drum water level fluctuates. Therefore, the choice of ψ can be adjusted according to the actual controlled plant.

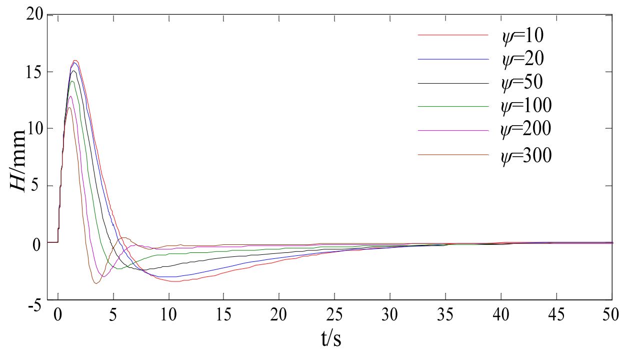

Fig. 8. Effect of ψ on the drum water level.

4.3 Feed water flow rate disturbance

Boiler feed water flow rate plays a key role in the regulation of drum water level. In the process of drum water level regulating, feed water flow rate is easy to fluctuate because of the influence of feed water heaters, pipe, valves and other equipment.

In order to discuss the control performance of the controller proposed in this paper under the disturbance of feed water flow rate, the feed water flow rate sine disturbance simulation test is carried out. The frequency of sine disturbance is 0.1, and the amplitude is 10%. The simulation result is shown as Fig. 9.

The LADRC-GCC can effectively suppress the disturbance caused by the feed water flow rate, and the drum water level is the most stable. The control effect of LADRC is better than that of NLADRC. The fluctuation of LADRC is slow, and the amplitude and frequency of NLADRC are the largest. Therefore, in case of rapid fluctuation of feed water flow rate, the control performance of LADRC-GCC is much better than the other two kinds of traditional controllers.

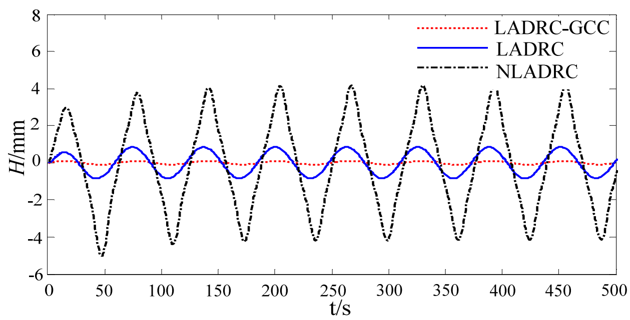

Fig. 9. Drum water level dynamic characteristic under the sine disturbance of feed water flow rate.

The compensation coefficient of GCC is shown as Fig. 10, when the feed water flow rate fluctuates rapidly, K can change rapidly, mainly because the observation error of LESO changes rapidly, then the output of compensation controller can be adjusted rapidly, and the feed water flow rate is adjusted rapidly.

The outputs of LESO are shown as Fig. 11, LESO of LADRC-GCC can accurately observe the position change and speed change of drum water level, and then adjust the compensation controller output of GCC to realize the accurate and rapid regulation of feed water flow rate.

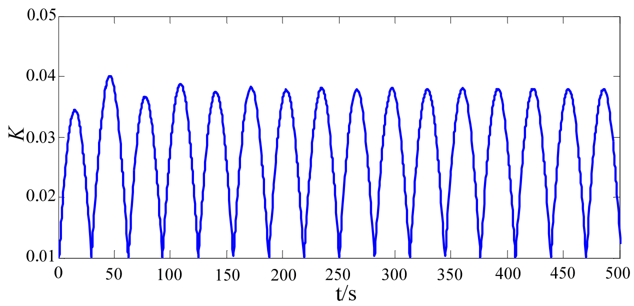

Fig. 10 *K* changes under the sine disturbance of feed water flow rate.

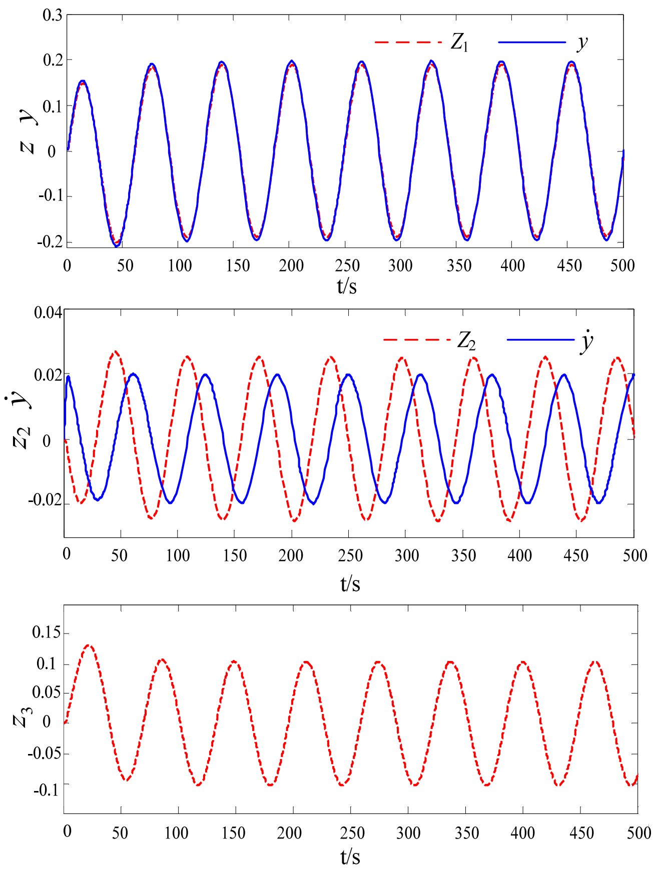

Fig. 11 LESO outputs under the sine disturbance of feed water flow rate.

CONCLUSION

(1) In this work, boiler drum water level LADRC-GCC controller is proposed based on the LADRC and combined with the gray correlation calculation method. The GCC compensation coefficient is calculated by the absolute value of difference between output of the model and its observation value.

(2) Furthermore, the disturbance simulation tests are carried out, results show that the LADRC-GCC can compensate various disturbances in time, whether it is the disturbance of feed water flow rate or main steam flow rate, and its control performance is much better than the LADRC's and NLADRC's.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

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