Drum Water Level Control System of Sintering HRSG based on Modified ADRC Controller

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Abstract. In this paper, a modified adaptive disturbance rejection control (ADRC) method was proposed and applied in sintering heat recovery steam generator (HRSG) drum water level control system to overcome the strong disturbance effect. The system adopted three-element cascade control scheme, which employed PID controller in the inner loop to rapidly eliminate the feed-water disturbance and the modified ADRC controller in the outer loop to overcome disturbances from flow rate of steam and perturbations of boiler-drum water level. With the proposed control scheme, the system can keep stable and maintain satisfied control result under the influence of different disturbance signals. Simulation results show that, compared with the traditional PID-PID and ADRC-PID cascade control, the modified ADRC-PID control strategy has better dynamic regulation performance and robust quality.

Keywords: ADRC, HRSG, water-level in drum, three-element cascade control scheme;

1. INTRODUCTION

Sintering heat recovery steam generation (HRSG) is an effective way to reasonably utilize sintering waste heat. During its working process, it is important to keep sintering waste heat boiler drum water level tightly within the desired range to prevent over-heating of boiler components or flooding of steam lines. Since HRSG is a complex industrial process with many disturbance factors, strong nonlinearity and large time delay, which will cause drum water level fluctuating frequently during operation, it is necessary to employ effective control scheme to maintain drum water level stable under disturbances and system uncertain conditions.

The popular way to stabilize drum water level during operation is three-element control system, which is a compound control system of feedforward and cascade feedback control scheme. In three-element control system, the inner loop uses feed water flow as the feedback signal to reject feed water disturbance quickly, the outer loop uses water level as the feedback signal to stabilize water level effectively, and the feedforward control changes the feed water flow according to steam flow signal. Normal three-element control strategy employed PID controllers for inner and outer feedback loops. However, as the increase of boiler volume, the drum volume becomes relatively smaller, and it becomes more and more difficult to achieve satisfactory control performance with the traditional PID control method [1]. Prior drum water level controller designs have been performed with the emphasis on the robustness and adaptability. In [2], a varying parameter control method is conducted to deal with nonlinear and time variant dynamics of water level control system, but it is difficult to regulate controller parameters to achieve satisfactory performance for different system with this method. In [3-4], the Smith estimation and general predictive control (GPC) method are used to improve control performance, but the method relies on accurate system mode, and the control effort may be invalid in case of system model mismatch. In [5], a sliding mode control (SMC) for boiler drum water level is compared with optimal H_∞ controller to achieve better dynamic performance, but the sliding mode control method still exhibits unavoidable chattering response. In [6-9], artificial intelligence based on fuzzy control and neural network algorithms are used in controller parameters on-line tuning. The resulted controller can achieve good robustness and dynamic response at the same time but the method need large calculation and is difficult to realize real-time control in industrial application.

Adaptive disturbance rejection control (ADRC) is a new practical robust controller constructed by Han Jingqing and others on the basis of classical PID controller [10,11]. ADRC has low requirement on model precision, can effectively observes and compensates the coupling disturbance between variables through the extended state observe (ESO), and is robust to external disturbances and system uncertainty. Therefore, it displays good performance in the control of drum water level. However, the output of the traditional ADRC control law is not smooth and has the characteristics of sharp variation point due to its nonlinear property, which is easy to cause oscillation in the control process and should be avoided in the drum water level control system of sintering waste heat boiler. To solve this problem, [12] adopted the linear / nonlinear switching ESO, [13] changed the nonlinear function *fal()* in ADRC, to improve smooth output, and achieved good application effect. However, due to the strong disturbance and uncertainty characteristics of

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sintering waste heat boiler, it is still difficult to achieve ideal control effect.

In this paper a modified ADRC control law is proposed to achieve satisfied control quality of the system. The nonlinear function *fal()* in ESO and Non-linear State Error Feedback Controller (NLSEF) are revised to overcome the dynamic chattering during transient and disturbance rejection period. At the same time the three impulse cascade control system is still employed to reject feed water disturbance quickly and stabilize water level effectively. The control result of the proposed method is compared with traditional PID-PID and PID-ADRC methods to verify its effectiveness.

The remainder of this paper is organized as follows. Section 2 introduces the basic principle of normal ADRC method. Section 3 presents the proposed modified ADRC control algorithm. Section 4 builds the system model for simulation analysis. Then, simulation results, demonstrating the effectiveness of proposed control scheme, are given in Section 5. Finally, Section 6 contains concluding remarks.

2. BASIC PRINCIPLE OFADRC

The scheme of ADRC is presented in Fig.1， where *w(t)* denotes external disturbance applied to the objective. ADRC consists of three modules: Tracking differentiator (TD), Extended State Observer (ESO), and Non-linear State Error Feedback Controller (NLSEF).

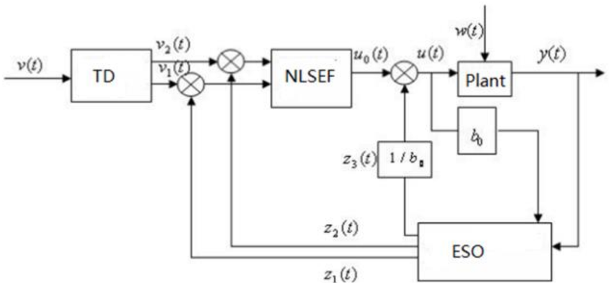

Fig.1 ADRC control structure

The TD module is used to extract the differential signal of the reference to avoid large overshoot during fast transient process. It is designed based on fast discrete tracking differentiator method and can be presented as

$$\begin{cases} v_1(k+1) = v_1(k) + hv_2(k) \\ v_2(k+1) = v_2(k) + hfhan[v_1(k) - v(k), v_2(k), r, h] \end{cases} \tag{1}$$

where v is the desired water level, v_1 and v_2 represent the anticipative dynamic procedure for water level and its change rate, h the integral step, r the tracking operator, and the function $fhan(x_1,x_2,r,h)$ is the optimal synthetic rapid control function, which is defined as

$$fhan = \begin{cases} -rsgn(a) & |a| > \delta \\ -r\dfrac{a}{\delta} & |a| \le \delta \end{cases} \tag{2}$$

where

$$a = \begin{cases} v_2(k) + \dfrac{a_0 - \delta}{2} sign(y(k)) & |y(k)| > \delta_0 \\ v_2(k) + hy(k) & |y(k)| \le \delta_0 \end{cases}$$

$$a_0 = \sqrt{\delta^2 + 8r|y(k)|}, \quad \delta = rh, \quad \delta_0 = \delta h,$$

$$y(k) = v_1(k) - v(k) + hv_2(k)$$

The ESO module is used to estimate the states in the system, and the internal and external disturbances of the system model. It is represented as

$$\begin{cases} e(k) = z_1(k) - y(k) \\ z_1(k+1) = z_1(k) + h[z_2(k) - \beta_{01}e(k)] \\ z_2(k+1) = z_2(k) + h\{z_3(k) - \beta_{02}fal[e(k),1/2,\delta] \\ \qquad + f_0[z_1(k), z_2(k)] + b_0u(k)\} \\ z_3(k+1) = z_3(k) - h\beta_{03}fal[e(k),1/4,\delta] \end{cases} \tag{3}$$

In HRSG drum water level control system, the output z_1 express the estimation of water level y, z_2 the estimation of change rate of water level, and z_3 the estimation of lumped disturbance and unmodeled states in the system. $f_0()$ represents the known part expression of the system model. The adjustable parameters $\beta_{01}, \beta_{02}, \beta_{03}$ are the correction gains of output error. Their value will influence the ESO convergence performance. *fal()* is a nonlinear function with the parameter δ as a linear interval width.

The control signal u is calculated by NLSEF module as

$$\begin{cases} e_1(k+1) = v_1(k+1) - z_1(k+1) \\ e_2(k+1) = v_2(k+1) - z_2(k+1) \\ u(k+1) = u_0(k+1) - \dfrac{z_3(k+1) + f_0[z_1(k+1), z_2(k+1)]}{b_0} \\ u_0(k+1) = \beta_1 fal[e_1(k+1), a_1, \delta_1] + \beta_2 fal[e_2(k+1), a_2, \delta_1] \end{cases} \tag{4}$$

where e_1 is error of the desired output and estimated output, and e_2 the output change rate error. a_1, a_2, δ_1 the adjustable parameters of nonlinear function *fal()*, u_0 the output of NLDEF, b_0 the compensation parameter, and u the control signal.

3. MODIFIED ADRC ALGORITHM

ESO and NLSEF are the two important modules of ADRC. In ESO module, both the internal and external disturbances are extended as a new state. By properly choosing the parameters of nonlinear function *fal()*, all the states, including internal and external disturbances, can be estimated in ESO. In the controller module NLSEF, *fal()* is also employed to construct nonlinear control law. It can be seen that *fal()* is the core unit of nonlinear ADRC algorithm. The definition of *fal()* is actually a mathematical fitting based on the control engineering experience: large error with small control gain while small error with large control gain. In the conventional ADRC control algorithm, the nonlinear function *fal()* is defined as

$$fal(e,a,\delta)=\begin{cases}|e|^{a}sign(e) & |e|>\delta\\ \dfrac{e}{\delta^{1-a}} & |e|\le\delta\end{cases} \quad (5)$$

where e is the error signal input, a,δ the parameters of the nonlinear function *fal()*.The characteristic of *fal()* is shown in Fig.2. In the boiler drum water level control system, to guarantee control accuracy and restrain water level oscillation, the parameters a,δ need to be chosen properly. Normally, a value should satisfy $0<a<1$, to generate large control gain for small input error, and small control gain for large input error.

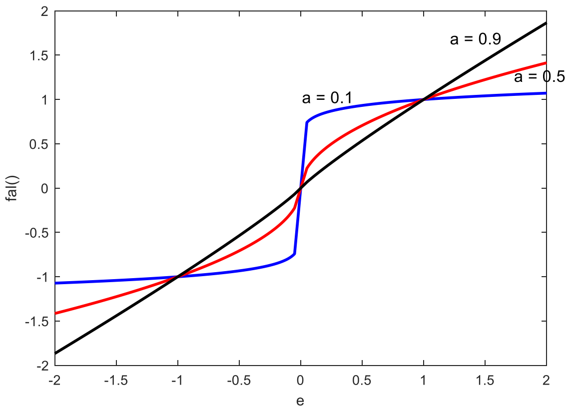

Fig. 2 Characteristic plot of traditional *fal()* function

It can be seen from Fig. 2 that *fal()* is a linear function when $|e|\le\delta$, the curve slope is determined by value of a,δ. As $a,\delta<1$ normally, the control gain is a large value in this range. While, when $|e|>\delta$, *fal()* is a nonlinear exponential function, which means that the control gain become smaller as error increase, and the control gain will further decrease with the parameter a decreases. Many simulations and experiments showed that by using nonlinear function *fal()* and tuning a,δ properly, the control system can attenuate the oscillation caused by large disturbances and improve the stability and robustness of the system effectively [11].

However, it also can be seen from Fig. 2 that the characteristic of function *fal()* is not smooth. There is a inflection point at $|e|=\delta$. The sudden change of the function characteristic may cause chattering problem and result in water level fluctuation. To solve this issue, the non-smooth function *fal()* is replaced by a smooth logarithmic function *faln()* with similar characteristic in the ESO and NLSEF module. The new function *faln()* is expressed as

$$faln(e,c)=log_c(|e|+1)*sign(e) \qquad (c>1) \qquad (6)$$

where c is the tuning parameter to determine the curve shape of function *faln*(). The characteristic of the new function *faln()* is shown in Fig. 3.

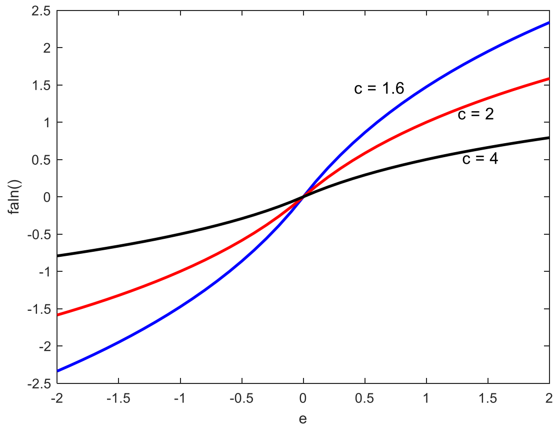

Fig. 3 Characteristic plot of modified faln() function

The ESO and control signal in NLSEF module can be redefined as equations (7) and (8) respectively with the revised function *faln()*

$$\begin{cases}e(k)=z_1(k)-y(k)\\ z_1(k+1)=z_1(k)+h[z_2(k)-\beta_{01}e(k)]\\ z_2(k+1)=z_2(k)+h\{z_3(k)-\beta_{02}faln[e(k),c_{o1}]\\ \qquad +f_0[z_1(k),z_2(k)]+b_0u(k)\}\\ z_3(k+1)=z_3(k)-h\beta_{03}faln[e(k),c_{o2}]\end{cases} \quad (7)$$

$$u_0(k+1)=\beta_1 faln[e_1(k+1),c_1]+\beta_2 faln[e_2(k+1),c_2] \quad (8)$$

With the new nonlinear function *faln()*, a modified ADRC algorithm is constructed based on smooth feedback control and observer function. The control result with the new ADRC algorithm can be improved consequently. Furthermore, the number of tuning parameters is also decreased accordingly, which simplify the controller design process.

4. DRUM WATER LEVEL CONTROL BASED ON MODIFIED ADRC_ PID CONTROLLER

The boiler drum water level control is a sluggish system with different sources of disturbances. When it is controlled using conventional single loop with water level as feedback signal, there will be large deviation during transient process, especially for steam flow disturbance, where the controller will behave under false water level detection and result in large oscillation of drum water level.

To monitor and maintain the water level effectively, three-element control strategy is designed and implemented for water level control system. The block diagram of the control scheme is shown in Fig. 4, where H and H_0 represent the actual and set drum water level respectively; $G_W(s)$ and $G_D(s)$ represent the transfer function of feed water flow and steam flow to water level respectively; γ_D, γ_W and γ_H are the transfer parameters of steam flow, feed water flow and drum water level transducers respectively; α_D and α_W are the division factors of the steam flow and feed water flow, and K_Z and

K_u are the characteristic factor of the actuator and valve respectively[14,15].

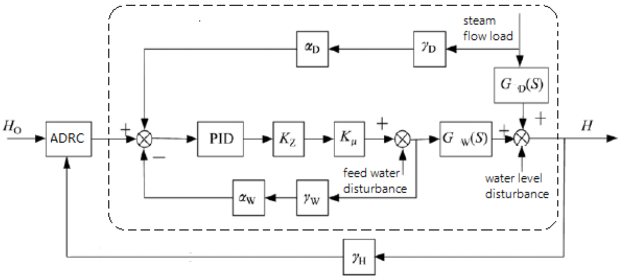

Fig. 4 Block diagram of the control scheme

The control scheme is composed of feedforward control structure and cascade feedback control structure based on the measured values of three process parameters: drum water level, feed water flow and steam flow. In the control system, the drum water level is the controlled variable, the feed water supplied to the drum is treated as control signal to keep water level stable. As the presence of steam below the liquid level in the drum causes the shrink-and-swell phenomenon, feedforward control is necessary in the system. The saturated steam taken from the drum to the super heaters and to the turbine eventually, is used as the feedforward signal of the control system, which will change the feed water flow without waiting for actual level to change. During industrial operation, disturbances may come from all these three elements, which makes it important to reject the disturbances effectively. Thus, the cascade feedback control loop is employed, where the inner loop uses feed water flow as the feedback signal to reject feed water disturbance quickly, and the outer loop uses water level as the feedback signal and employs the ADRC control law to stabilize water level effectively under large uncertain disturbances. The error signal comprises water level and feed water flow error. The water level error is based on the difference between the set level H_0 and the actual drum water level H, while the flow error is based on the feed water and the steam flow rate difference. The error signals are fed to ADRC and PID controllers of outer loop and inner loop respectively and the controller output regulates the feed water control valves to change feed water flow rate.

5. SIMULATION RESULT

Consider a normal boiler drum water level system model as following:

$$\begin{cases} G_W(s) = \dfrac{H(s)}{V_W(s)} = \dfrac{0.037}{30s^2 + s}; \\ G_D(s) = \dfrac{H(s)}{V_D(s)} = \dfrac{3.045s - 0.037}{15s^2 + s}; \\ \alpha_D = \alpha_W = 0.083, \gamma_D = \gamma_W = 0.21, \\ \gamma_H = 0.033, K_Z = 10, K_u = 2; \end{cases}$$

The system is simulated in matlab/simulink with cascade three-element control strategy as shown in Fig. 5.

The ESO of ADRC estimates the states of the system based on measured drum water level H and the control signal u. The estimated states and TD output are sent to NLSEF controller, which will calculate the set point value for feed water flow regulator of inner loop. At the same time, the steam flow is feedforwarded to the inner loop to compensate the large water level deviation during transient period caused by shrink-and-swell effect by steam flow disturbance.

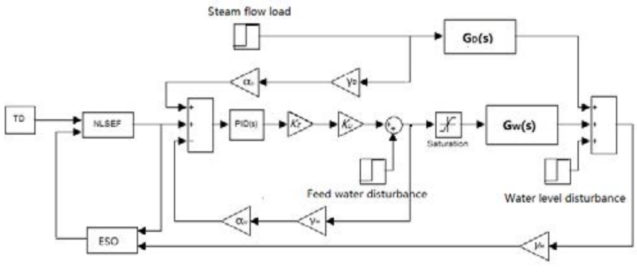

Fig. 5 Block diagram in simulink

To verify the effectiveness of the proposed modified ADRC three-element control scheme, it is compared with the conventional PID-PID control method, and normal ADRC-PID control method.

In PID-PID control scheme, PID controllers are employed for both inner and outer loop. The PID parameters are tuned based on the consideration of tracking performance, inner and outer disturbance rejection and system stability. The final parameters are selected as K_{p1}=5、K_{i1}=0.0033, K_{p2}=50、K_{i2}=0. where K_{p1} and K_{i1} are the proportional and integral parameters of outer loop respectively, K_{p2} and K_{i2} are the proportional and integral parameters of inner loop respectively.

For normal ADRC-PID control method, the inner loop still use PID controller while the outer loop employs normal ADRC controller to achieve better disturbance rejection and tracking performance. The parameters of ADRC controller include parameter r in TD unit to control tracking reference change rate, tuning gains β_{01}、β_{02}、β_{03} and disturbance compensation parameter b0 in ESO and the tuning gains β_1 and β_2 in NLSEF. The parameters initial value can be set according to [16] and fine tuned during simulation process. The final value of the parameters are selected as β_{01}=50, β_{02}=1800, β_{03}=15, β_1 =25, β_2 =1000, b_0=0.5.

In the proposed modified ADRC-PID control method, same PID controller is used in the inner control loop while the modified ADRC controller is employed in the outer loop, replacing the normal ADRC controller. Compared to the normal ADRC controller, the modified ADRC controller change the format of *fal()* function in the ESO and NLSEF modules, where the non smooth function f*al()* in equation (5) is replaced by a smooth logarithmic function *faln()* in equation (6) with similar characteristic. The new parameters for modified ADRC control scheme is the parameters c_1, c_2 of function *faln()* and their corresponding gain . After online tuning, the parameters are selected as $c_1=100$, $c_2=4.5$, $\beta_1=180$, $\beta_2=500$.

In simulation test, the proposed modified ADRC-PID control method is compared with the normal ADRC-PID control method and the conventional PID-PID control method to verify its effectiveness. The simulation result of the three control methods on the nominal system model is shown in Fig. 6.

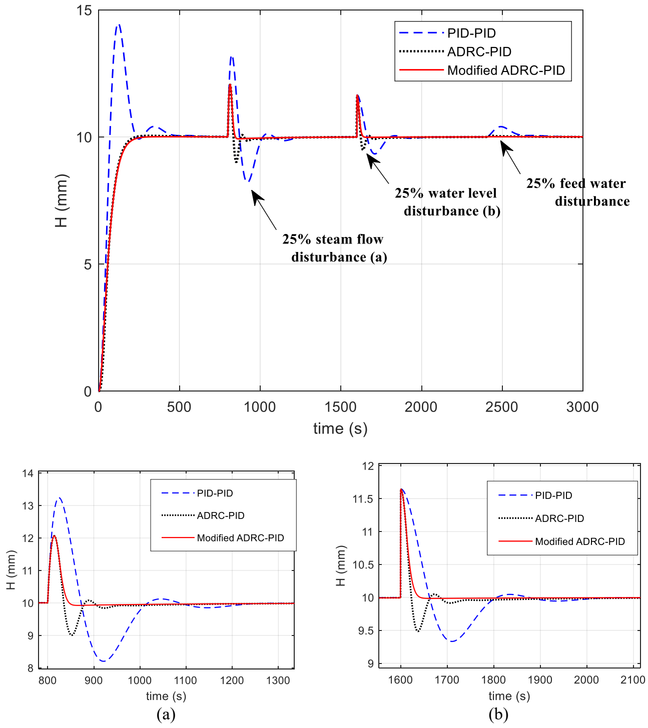

Fig. 6 Simulation result of drum water level control system ((a) Zoom-in of system response with 25% of steam flow disturbance, (b) Zoom-in of system response with 25% of water level disturbance)

In Fig. 6, the solid line, dashed line and dotted line represent the simulation results with modified ADRC-PID, normal ADRC-PID and conventional PID-PID control methods respectively. It can be seen that the transient over shoot is about 40% for conventional PID-PID cascade control scheme. While for the normal and modified ADRC-PID control schemes, there is no overshoot in transient period thanks to the pre-designed reference trajectory calculated by TD module. For PID-PID control method, because of the oscillation after over shoot, the system enter steady state at about 500s, while for normal and modified ADRC-PID control methods the system enter steady state smoothly at about 250s. It can be concluded that the transient time decreased about 50% by employing ADRC control scheme.

For three-element control system of boiler drum water, disturbances come from all of the three elements and it is important to guarantee the system working performance under different disturbances. To verify the disturbance rejection capability of the system, disturbances are injected in the simulation process. 25% of steam flow disturbance (*D* in Fig.4) is added at 800s, 25% of water level disturbance (*H* in Fig. 4) is added at 1600s, and 25% of feed water flow disturbance (*W* in Fig. 4) is added at 2400s.

From the simulation result in Fig. 6, it can be seen that all the three methods can reject the inner disturbance W (feed water flow) effectively. While for outer disturbances *D* and *H*, the system performance are very different for the three methods. For PID-PID control method, it can reject the disturbance from *D* and *H* eventually, but the oscillation amplitude and time is the largest. For normal ADRC-PID control method, the oscillation amplitude and time decreased greatly and for the proposed modified ADRC-PID control method, the water level chattering amplitude and time are further decreased. There is almost no chattering and the water level change smoothly during disturbance rejection process. Steam flow disturbance settling time is further reduced to about 100s, and water level disturbance settling time to about 50s, which means the settling time decreased about 50% and more than 60% for steam flow and water level disturbance cases respectively compared to the normal ADRC-PID method.

To verify the robustness of the proposed control system, simulations were done under system model mismatch condition. Firstly, the time constant and model gain of $G_W(s)$ and $G_D(s)$ in equation (10) and (12) were increased by 30% while the controller parameters keep unchanged. The simulation result is shown in Fig. 7, with the solid line, dashed line and dotted line represent the simulation results with modified ADRC-PID, normal ADRC-PID and conventional PID-PID control methods respectively.

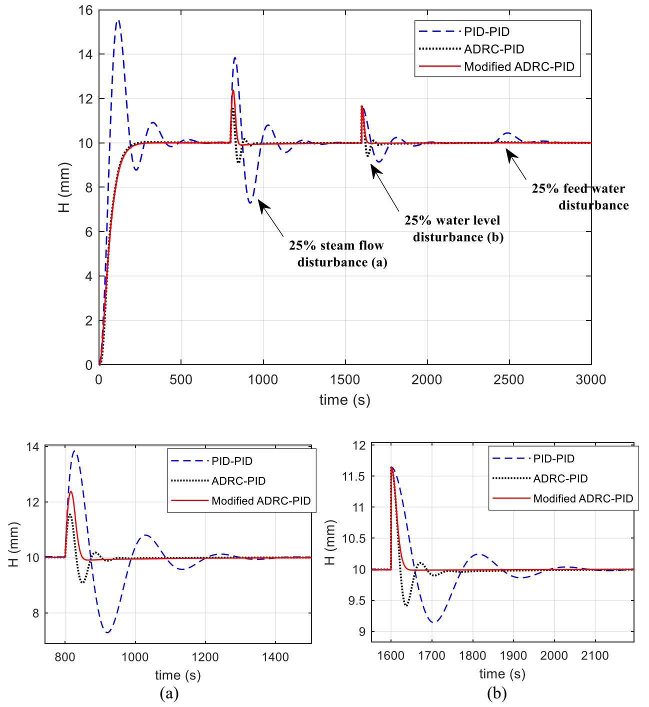

Fig. 7 Simulation result of drum water level control system under model mismatch condition. ((a) Zoom-in of system response with 25% of steam flow disturbance,(b) Zoom-in of system response with 25% of water level disturbance)

It can be seen that under condition of model parameter increased, PID-PID control method shows largest oscillation in transient and disturbance rejection period. Normal ADRC-PID method can reduce the settling time greatly, and the proposed modified ADRC-PID control method exhibits the best working performance with the smallest oscillation and settling time of about 50s, which is similar as the simulation result of nominal system model

Secondly, the time constant and model gain are increased and decreased by 30% respectively and the controller parameter of the modified ADRC-PID controller keep unchanged. The simulation result is shown in Fig. 8 with the solid line represent the simulation result of model parameter increased, dashed line represent the simulation result of model parameter decreased, and the dotted line represent the simulation result of nominal model. In the simulation process, 25% of steam disturbance was added at 800s, 25% of water level disturbance was added at 1600s, and 25% of feed water disturbance was added at 2400s.

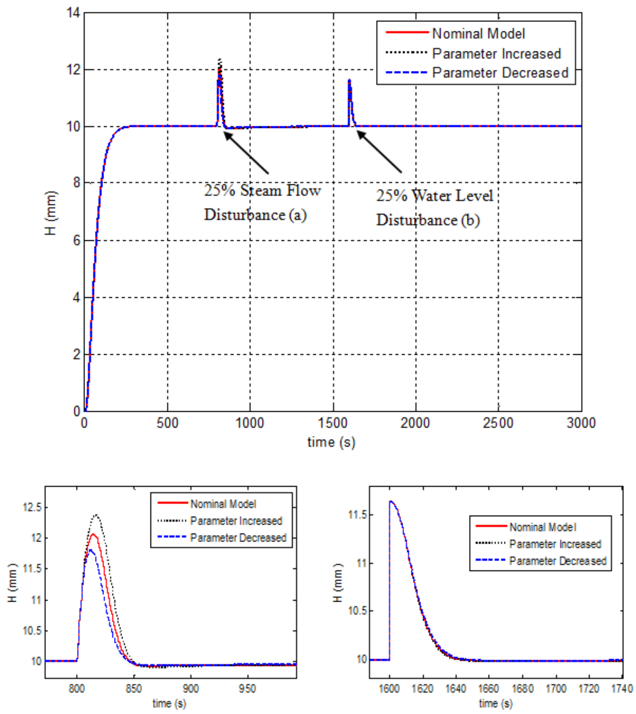

Fig. 8 Simulation result of modified ADRC-PID control method with model mismatch conditions. ((a) Zoom In of system response with 25% of steam flow disturbance,(b) Zoom In of system response with 25% of water level disturbance)

It can be seen that with the proposed modified ADRC-PID control method, for nominal model, parameters increased, and parameters decreased cases the control performances are similar. Therefore, the proposed modified ADRC-PID control method can keep similar control performance under nominal and model mismatch conditions, which verify its good robustness and disturbance rejection capability.

6. CONCLUSION

In HRSG boiler system, it is important to perfectly stabilize drum water level to prevent over-heating of boiler components or flooding of steam lines. During industrial operation, disturbances, model uncertainties and parameter mismatch due to variant operating conditions will affect water level stabilization. In this case, a modified ADRC controller based three-element control scheme is proposed in this paper to overcome dynamic chattering during transient and disturbance rejection period. Simulation results show that with the proposed control scheme, the water level fluctuation during disturbance rejection period disappeared, and the settling time was reduced more than 50% compared to normal ADRC control method. Simulations under model parameter varying conditions also show that the proposed method has satisfied robustness and disturbance rejection performance in model mismatch case.

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