ICIC Express Letters
Part B: Applications
Volume **8**, Number **10**, October **2017**

ICIC International ©2017 ISSN 2185-2766
pp. 1409–1419

A NOVEL CONTROL STRUCTURE FOR MAIN SUPERHEATED TEMPERATURE CONTROL SYSTEM

Wei Yang[1], Qingwei Meng[2], Yuguang Niu[1] and Zhenfang Zhong[2]

[1]School of Control and Computer Engineering
North China Electric Power University
No. 2, Beinong Road, Changping District, Beijing 102206, P. R. China

[2]College of Information and Control Engineering
China University of Petroleum (Huadong)
No. 66, Changjiang West Road, Huangdao District, Qingdao 266580, P. R. China
mqw@upc.edu.cn

Received May 2017; accepted July 2017

Abstract. *Delay, parameters time-varying and uncertainty exist abroad in industrial process control systems such as power units and chemical reactors. In order to get good control performance in these systems, a new control structure, named weighted double loop control structure (WDLCS), is proposed in this paper. The selection strategy of the weighting factors is discussed. A special WDLCS using Smith predictor as its rear loop is introduced in detail. Then, robustness analysis of the composite structure is given. At last, the effectiveness of the WDLCS is tested by a lot of simulations and its application in the superheated temperature control system.*
Keywords: Weighted double loop control structure, Time delay, Time-varying parameters, Uncertainty systems, Superheated temperature control systems

1. **Introduction.** Delay, time-varying parameters, uncertainty are common in industrial control processes. In general, the plant's uncertainties include unpredictable parameter variation, and unmodeled plant nonlinear dynamics [1,2]. The difficulties caused by those characteristics have been recognized for a long time. In such situations, the usual controller and control structure are inadequate to achieve desired performance [3]. The problems of controlling such systems have been attracting the attention of many researchers and many methods have been presented [4]. One of the primary methods is adaptive control [5,6]. In this method, the parameters of a controller, which is selected as priori knowledge, are updated using recursively estimated parameters of the plant. Then, time delay control (TDC) which focuses on practical issues rather than adjusting control gains like adaptive control or identifying model parameters is studied well [7,8]. Moreover, sliding mode control (SMC) [9], learning control [10] and delay observers [11-13] are also proposed for such systems.

As is well known that, together with the increasing expectations of dynamic performances, engineers need their models to behave more like the real process. If no model can be used, processes often cannot be controlled effectively by just using the simple single-loop. In order to get good control performance, model identification is necessary. The precise model is difficult to achieve, but an inexact model is easy to be obtained. Though the model is inexact and includes unknown dynamics, it is still better than no model.

With an exact model, the Smith predictor is popular as an effective dead-time compensator for a stable process with long time-delay [14]. Many controllers are designed based on the application of the Smith predictor [15-17]. Different modifications have been proposed [18,19]. The performance of the Smith predictor is affected by the accuracy model which represents the plant. To overcome this problem by taking full advantage of existing inexact reference models, a weighted double loop control structure (WDLCS) is proposed. In the new structure, the reference model may be inexact and usually inexact, but it works well. The output of the reference model and the output of actual closed-loop are weighed as the WDLCS's feedback value. The selection strategies of the weighting factor are discussed in different situations. The WDLCS has good performance in controlling the plant with time-varying and uncertainty. Besides, to improve performance, a special composite structure using the Smith predictor as its rear-loop is introduced in detail. The robust performance of the composite structure is analyzed. The effects of the parameters variation and model accuracy are studied by using a first-order plus dead time (FOPDT) plant. The effectiveness of the composite structure is proved by using it in the super-heated temperature control system.

2. The New Control Structure.

2.1. Weighted double loop control structure (WDLCS).

The process with delay in feedback channel is difficult to control. The reason is not from the controller but from the feedback. The problem comes from the feedback's lag. So, to overcome the difficulty, we should focus on the feedback value. In general, the control structure is shown in Figure 1. Its feedback value is $\tilde{y}$. For the same plant only without delay, it is shown in Figure 3 with feedback value $\bar{y}$. From comparision with the two feedback values, we find that the anti-delay performance in Figure 1 will perform better if its feedback value $\tilde{y}$ is close to the feedback value $\bar{y}$. The general feedback control structure is shown in Figure 1 with feedback value $\tilde{y}$. The ideal structure for anti-delay is shown in Figure 3 with feedback value $\bar{y}$. $\bar{y}$ is the delay-free value of $\tilde{y}$. In general, the ideal feedback cannot be realized in control, but we can do our best to make our feedback value closer to $\bar{y}$. So, a new control structure, named weighted double loop control structure (WDLCS), is designed and shown in Figure 2.

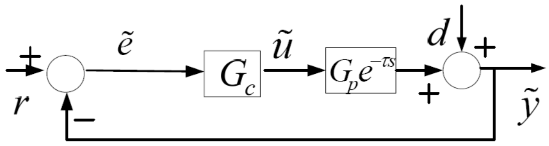


FIGURE 1. The general control structure

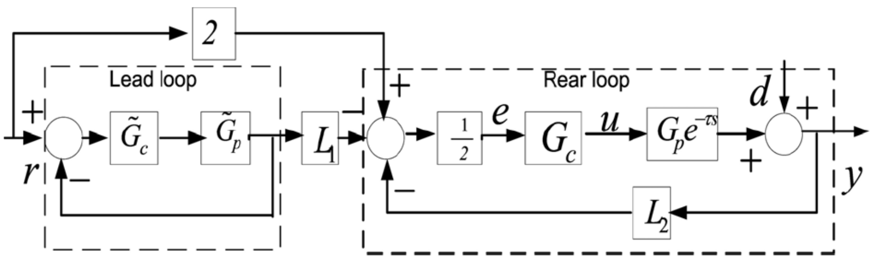


FIGURE 2. The weighted double loop structure

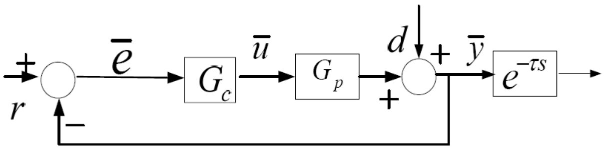


FIGURE 3. The ideal control structure

In Figure 1, the transfer function can be expressed as the following form:

$$\frac{\tilde{Y}(s)}{R(S)} = \frac{G_c G_p e^{-\tau s}}{1 + G_c G_p e^{-\tau s}} \tag{1}$$

And error $\tilde{e}$ is defined as:

$$\tilde{e} = r - \tilde{y} \tag{2}$$

In Figure 2, L_1 and L_2 are weighting factors. The relation of the factors is as follows

$$L_1 + L_2 = 2 \tag{3}$$

The WDLCS control error e is given by

$$e = [(r - L_2 y) + (r - L_1 y_1)]/2 \tag{4}$$

where,

$$y_1 = \frac{\tilde{G}_c \tilde{G}_p}{1 + \tilde{G}_c \tilde{G}_p} R(s) \tag{5}$$

In Figure 3, its error $\bar{e}$ is given by

$$\bar{e} = r - \bar{y} \tag{6}$$

where,

$$\bar{y} = \frac{G_c G_p}{1 + G_c G_p} R(s) \tag{7}$$

Assume $\tilde{G}_c = G_c$ and $\tilde{G}_p \approx G_p$, from Equation (4) and Equation (7), $y_1 \approx \bar{y}$ is easy to get, similarly, $e \approx \bar{e}$. Selecting e as the controller input is conducive to control, because the controller can get the changes of output faster than $\tilde{e}$. So, WDLCS can effectively overcome the impact of the delay on the control.

Remark 2.1. *Though the structure is designed considering delay, it also has the ability to reduce the impact, which is caused by other plant parameters' change, on the control performance. This conclusion can be obtained by the same error analysis method above.*

Remark 2.2. *In Figure 2, $(2r - L_1\tilde{y})/2$ can be interpreted as a new set-point. Thus, the new structure can also be seen as a control structure of set-point optimization. It makes the set-point accessible to avoid the set-point too aggressively.*

Remark 2.3. *At the same time, the new structure also has a very good characteristic which is that the controller can be designed based on an inexact plant model. The WDLCS will allow more freedom in choosing the structure of controller and controller parameters. That is to say, using the WDLCS can reduce the controller design complexity.*

2.2. **Stability analysis.** In Figure 2, the output is given by:

$$Y(s) = \frac{\frac{1}{2} L_2 G_c G_p e^{-\tau s}}{1 + \frac{1}{2} L_2 G_c G_p e^{-\tau s}} R'(s) \tag{8}$$

where,

$$R'(s) = \left(2 - L_1 \frac{\tilde{G}_C \tilde{G}_P}{1 + \tilde{G}_C \tilde{G}_p}\right) R(s) \tag{9}$$

The stability of lead-loop is easy to be realized. From Equation (8), the structure depended on the rear-loop with a stabilized lead-loop. The using pade approximation, the stability of Equation (8) can be solved by using exiting techniques such as the Routh-Hurwita criterion or the Nyquist stability criterion. The stability of system with pure delay analysis can be traced to [4,20]. The robustness will be discussed in the following section.

2.3. **Anti-disturbance performance.** Figure 2 shows that anti-disturbance performance of the system relies on the rear-loop. Open-loop gain of the rear-loop in Figure 2, is $L_2/2$ times as what it is when using the structure in Figure 1. With $L_1 > 0$ and $L_2 > 0$, $L_1 + L_2 = 2$, it is easy to show that $L_2/2 < 1$. Predictably, the anti-disturbance performance will fall. So, anti-disturbance performance becomes very important consideration when selecting the weighting factors. Relevant content will do further discussion later. In addition, it is common that disturbance cannot be identified, which means we cannot put a close disturbance to join lead-loop. This is also an important reason for anti-disturbance performance degradation.

This new control structure provides a way to improve the anti-disturbance performance. In order to improve anti-delay performance, L_2 and L_1 are assumed greater than zero. If only to improve anti-disturbance performance, the above assumption ($L_1 > 0$ and $L_2 > 0$) is unreasonable. If we make $L_1 < 0$, $L_2 > 2$ and ensure $L_1 + L_2 = 2$, it is easy to get $L_2/2 > 1$. The open-loop gain of the rear-loop in Figure 2 is greater than one. This means anti-disturbance performance improved.

2.4. **The selection strategy of weighting factors.** According to the above explanation, the WDLCS is able to reduce the influence of time delay. As a by-product, a selection strategy of weighting factors can be described as: to reduce the influence of time delay, L_2 should be chosen small as possible.

From Equation (8), it is known to all that the open-loop gain of the rear-loop is approximately equal to $L_2/2$. If L_2 is very small, it makes $L_2/2 << 1$, and then anti-disturbance will decline. To ensure certain anti-disturbance performance, L_2 should not be chosen too small. Now, another selection strategy of weighting factors can be described as: for disturbance rejection, L_2 should be chosen large as far as possible.

When the system is in steady state, the main function of controller is disturbance rejection; when the system is in dynamic, the main function of the control structure is to reduce the influence of delay. In view of the different situations, the dynamic weighted method is obtained: L_2 should be chosen small as possible in set-point tracking stage; L_2 should be chosen large as possible in steady state.

3. Composite Control Structure.

3.1. **A case of composite control structure.** The rear-loop can be any known control structure. In this paper, the structure performance of reducing the effect of time delay is what we focus on, and the Smith predictor is well known as an effective dead-time compensator for a stable process with large dead-time. Now, a case of composite control structure is shown in Figure 4. In this composite structure, the Smith predictor is added as the rear-loop.

The composite control structure is WDLCS plus Smith predictor structure. As mentioned previously, anti-delay characteristics of the composite structures become better than the Smith predictor. Moreover, because the composite control structure contains

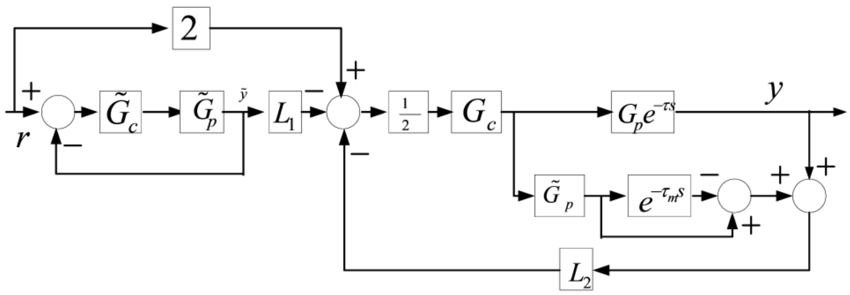


FIGURE 4. A composite control structure

the advantages of both the new structure in Figure 2 and the Smith predictor, it also has excellent properties to control the plant with time-varying parameters. In summary, the composite structure has a good control for plant with large-delay, time-varying. It only requires a plant model to work well, even if the model is inexact.

3.2. **Robustness analysis of the performance.** The composite structure is also robust to the parameter time-varying. An FOPDT transfer function model will be used to discuss the robustness of the structure:

The FOPDT is given by

$$P(s) = G_p(s)e^{-\tau s} = \frac{k_1}{T_1 s + 1} e^{-\tau s} \tag{10}$$

Prediction model is given by

$$P_m(s) = \tilde{G}_p(s)e^{-\tau_m s} = \frac{k_0}{T_0 s + 1} e^{-\tau_m s} \tag{11}$$

The characteristic equation of the system given in Figure 4 is:

$$\left[2 + L_2 G_c(s)\tilde{G}_p(s) + L_2 G_c(s)(P(s) - P_m(S))\right]\left[1 + \tilde{G}_c(s)\tilde{G}_p(s)\right] = 0 \tag{12}$$

With $\tilde{G}_c = G_c$, Equation (12) can be rearranged as:

$$2 + L_2 G_c(s)\tilde{G}_p(s) + L_2 G_c(s)\delta P(s) = 0 \tag{13}$$

where $\delta P(s) = P(s) - P_m(s)$.

From Equation (13), the $|\delta P(s)|$ can be obtained as follows:

$$|\delta P(s)| = \left| -\frac{2 + L_2 G_c(s)\tilde{G}_p(s)}{L_2 G_c(s)} \right| \tag{14}$$

If a PID controller is adopted, there is the ideal form of the PID:

$$\tilde{G}_c = G_c = k_p + k_i \frac{1}{s} + k_d s = \frac{k_d s^2 + k_p s + k_i}{s} \tag{15}$$

Substituting Equation (11) and Equation (15) in Equation (14):

$$|\delta P(j\omega)| = \frac{1}{L_2} \frac{\sqrt{\left[L_2 k_0 k_i - (2T_0 + L_2 k_0 k_d)\omega^2\right]^2 + [L_2 k_0 k_p + 2]^2 \omega^2}}{\sqrt{\left[k_i - (k_d + T_0 k_p)\omega^2\right]^2 + \left[(k_i T_0 + k_p)\omega - T_0 k_d \omega^3\right]^2}} \tag{16}$$

For $\omega \to 0$, $|\delta P(j\omega)| \to k_0$, thus, for low frequencies the norm bound uncertain region for $|\delta P(j\omega)|$ is given by the steady gain of the model k_0. The magnitude of the modeling error, $|P(j\omega) - P_m(j\omega)|$, is given by $|k_1 - k_0|$ at low frequencies. This shows that the closed-loop stability is only affected by uncertainties in steady state gains of the plant and plant model at low frequencies. Also it can be seen that very high modeling errors are allowed for maintaining the closed-loop stability.

For $\omega \to \infty$ $|\delta P(j\omega)| \to 0$, thus, at high frequencies, this implies that the choice of PID parameters does not affect the stability of the closed-loop system.

4. Case Study.

4.1. **Performance comparison of weighting factor changes.** In this section, an FOP-DT plant is considered. The FOPDT transfer function is

$$G_p = \frac{k_1}{T_1 s + 1} e^{-\tau s}.$$

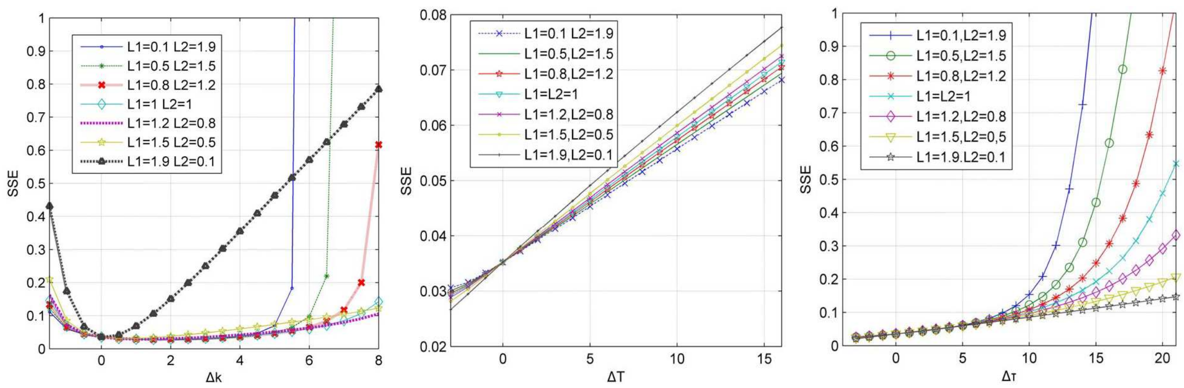
The identification of the plant is given by

$$\tilde{G}_p = \frac{k_0}{T_0 s + 1} e^{-\tau_m s} = \frac{2}{4s + 1} e^{-4s}.$$

PID controller is adopted, the controller parameters are given by: $K_p = 0.5$, $K_i = 0.08$, $K_d = 0.1$. Here, the parameters of the FOPDT plant k_1, T_1, τ are time-varying. The sum of square error (SSE) performance index is used to assess the performance of any control structure. The SSE performance index is given by: $G_{SEE} = \frac{1}{n}\sum_{t=1}^{n} e_t^2$. L_1 takes the value of 0.1, 0.5, 0.8, 1, 1.2, 1.5, 1.9, and correspondingly L_2 takes 1.9, 1.5, 1.2, 1, 0.8, 0.5, 0.1. In Figure 5, we have the following definitions: $\Delta k = k_1 - k_0$, $\Delta T = T_1 - T_0$, $\Delta\tau = \tau_1 - \tau_0$. About 400 simulation results of different weighting factors and parameters are shown in Figure 5. Form Figure 5(a), when L_1 is slightly bigger than L_2, their performance is better and has little difference. However, when $L_2 = 0.1$, $L_1 = 1.9$, its performance sharply descends.

From Figure 5(b), it can be seen that the choice of weighting factors has limited impact on raising the performance. From Figure 5(c), for anti-delay performance, it shows that the bigger L_1 is selected, the better the performance is. So when only considering anti-delay performance, L_1 should be selected as large as possible; however, when L_1 is too big, the performance descends in Figure 5(a). Of course, only considering the anti-disturbance performance, L_2 should be as big as possible; on the contrary, when L_2 is too big, the anti-delay performance descends in Figure 5(c).

When the system is in steady state, the main function of controller is disturbance rejection; when the system is in dynamic state, the main function of the control structure is to reduce the influence of delay. Figure 5 indicated that the selection of weighting factors is important for control system. For the same plant with different control section, different weighting factor is necessary.

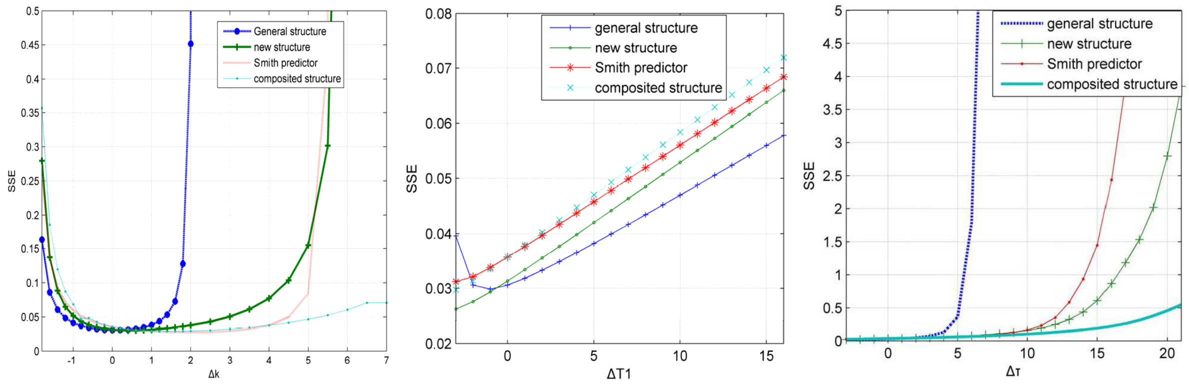


(a) (b) (c)

FIGURE 5. The composite structure's SSE contrast with different L_1 and L_2

4.2. **Performance comparison of parameter changes.** In this section, the simulation plant is the one using in Section 4.1. Among the three parameters k_1, T_1, τ, assuming that two of them are constant and can be accurately identified, the other one is time-varying. There are about 200 simulation results in Figure 6. The SSE performance of the four structures with $L_1 = L_2 = 1$ is compared in Figure 6, with one parameter changing. Here, general structure is the structure shown in Figure 1, WDLCS in Figure 2, composited structure in Figure 4.

Assuming $T_1 = 4$, $\tau = 4$, only the steady gain is time-varying. Plot the SSE curves of the four different structures in Figure 6(a), where $\Delta k = k_1 - k_0$ as the abscissa and the SSE performance index as the ordinate. When $-1 < \Delta k < 1$, namely, the model is



(a) (b) (c)

Figure 6. SSE contrast with parameters changing

accurate, the control effect is the best in the sense of the SSE. From Figure 6(a), it can be seen that differences begin to appear after $1 < \Delta k$. Accordingly, when k is time-varying and changes greatly, the composite structure (WDLCS with Smith predictor) shows better anti-time-varying characteristic than Smith predictor; the new structure (WDCLS with the rear-loop being general structure) is better than general structure.

The regulations represented in Figure 6(b) are easy, where $\Delta T = T_1 - T_0$. The only difference between the four structures' performance is in the order of 10^{-3}. Thence, the four structures' performances show difference, but very little.

From Figure 6(c), in the vicinity of $\Delta\tau = 0$, which means the model is accurate, and the control effect of the fours seldom differs. With the increase of $\Delta\tau$, the SSE trends of the general structure, Smith predictor and new structure begin to diverge one by one. This illustrates that the composite structure has a good anti-delay characteristic, especially, when the delay is large and time-varying.

In short, we can see that the control performance of new structure is better than general one, and the control performance of composited structure is better than Smith predictor in meaning of SSE. So it is obvious that using the WDLCS structure can improve the control performance of original structure.

4.3. **Application in the main superheated temperature control system.** A composite structure is applied in a main stream temperature control system with the properties of high inertia strong delay and time-variation. For the same process used by Fan et al. [21], the model of the process under different loads is proposed. As mentioned in this literature, the model is listed in Table 1.

In order to improve the control performance, the WDLCS is applied. The main stream tempeture control structure is shown in Figure 7. The composite structure is applied as the outer loop of the cascade control structure. The controller of the outer loop is PI

Table 1. Transfer function of superheated temperature process due to spray-water disturbance

Load	Leading section C (/kg/s)	Inertial section C (/kg/s)	Load	Leading section C (/kg/s)	Inertial section C (/kg/s)
37%	$-\frac{5.072}{(1+28S)^2}$	$-\frac{1.048}{(1+56.6S)^8}$	75%	$-\frac{1.657}{(1+20S)^2}$	$-\frac{1.202}{(1+27.1S)^7}$
50%	$-\frac{3.067}{(1+25S)^2}$	$-\frac{1.119}{(1+42.1S)^7}$	100%	$-\frac{0.815}{(1+18S)^2}$	$-\frac{1.276}{(1+18.4S)^6}$

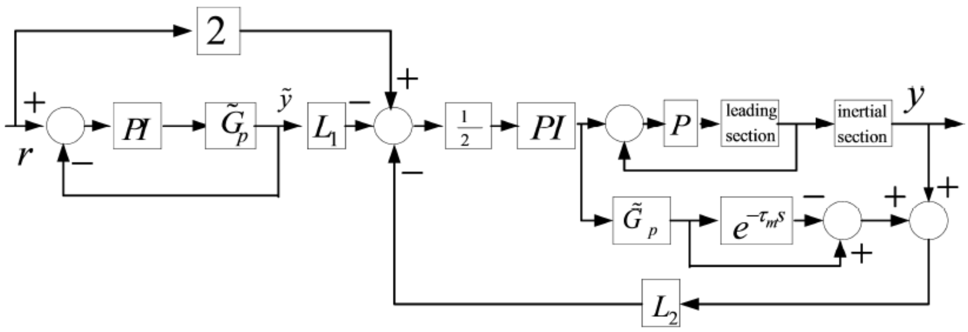
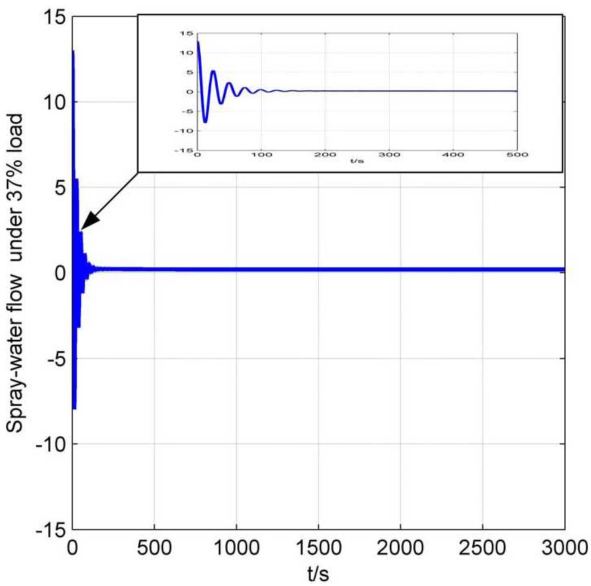
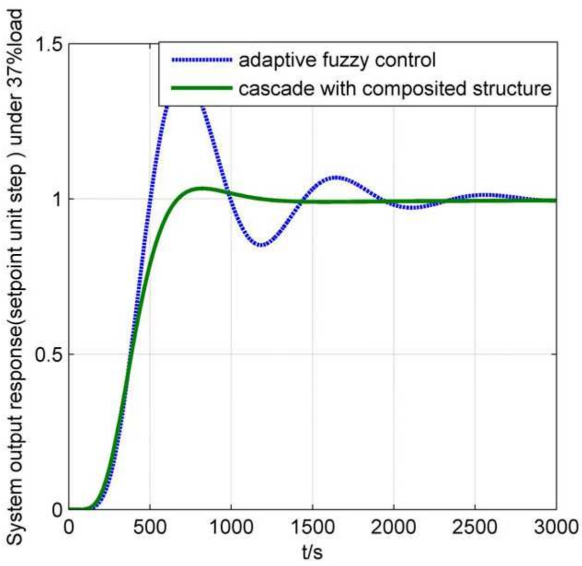


FIGURE 7. Main steam temperature control structure



(a) Sprary-water flow under 37% load



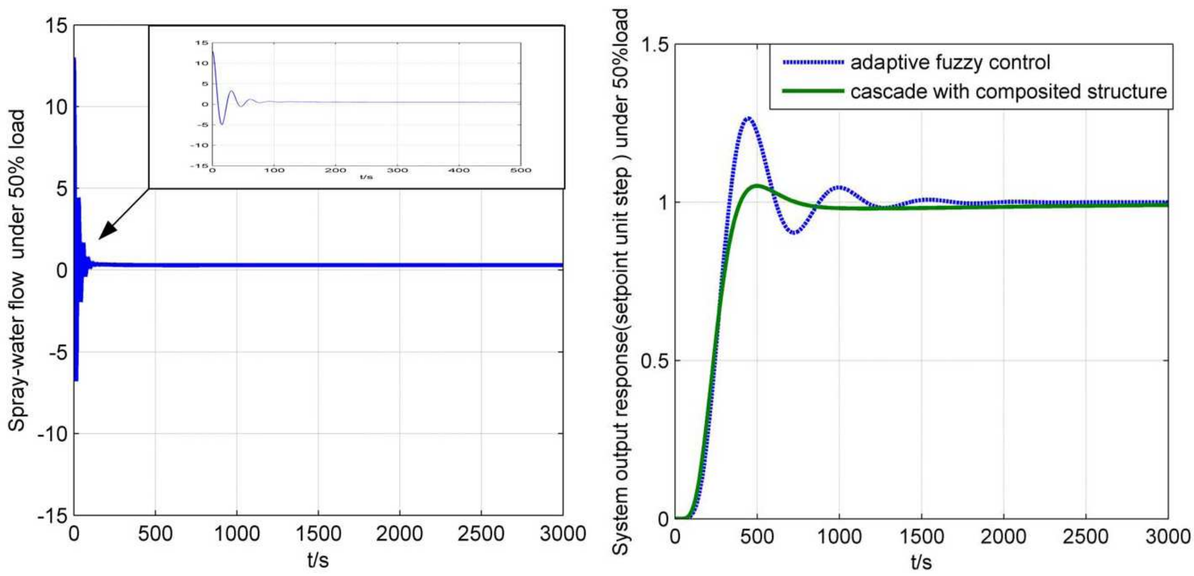
(b) System output response under 37% load

FIGURE 8. Main steam temperature control effect under 37% load

controller, and the parameters of the controller are given by: $k_{p1} = 1.3$, $k_{i1} = 0.005$. The inner loop controller is P controller with $k_{p2} = 10$. According to Section 2.4, the weighting factor is given by: $L_1 = 1.8$, $L_2 = 0.2$. Both the inertial section and inner loop under different loads are indentified as only one FOPDT transfer function: $1.1e^{-100s}/(262s+1)$.

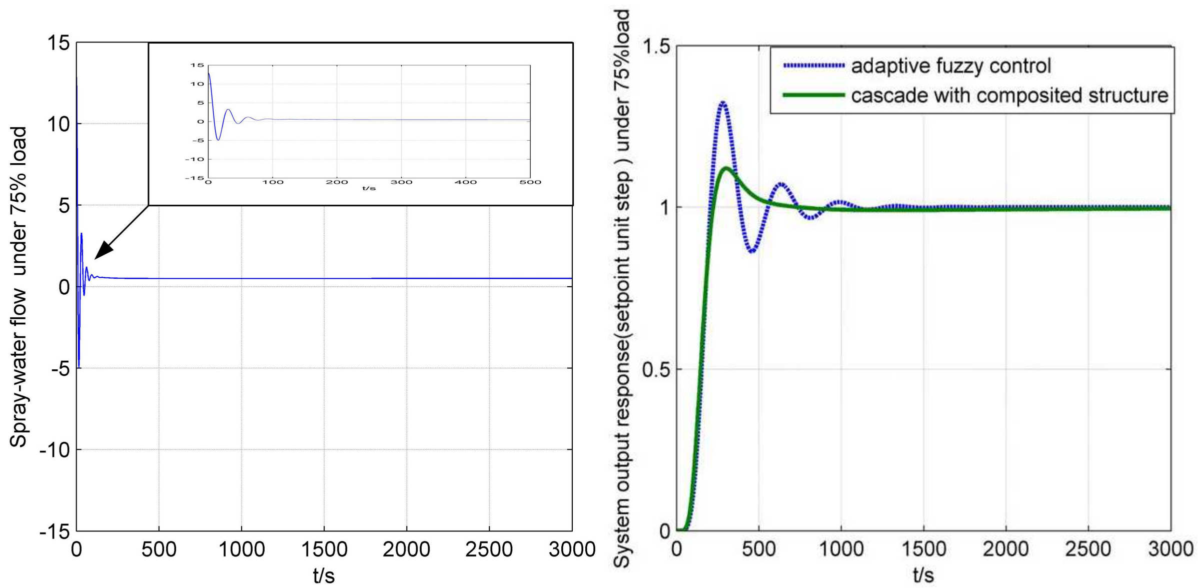
The adaptive fuzzy temperature control system is used in [21]. The control effect of WDCLS is compared with the adaptive fuzzy control. The system output unit step response of each method is represented in Figures 8(b)-11(b). Simultaneously, the changing curve of spray-water flow is represented in Figures 8(a)-11(a) when set-point is unit step. By comparison, it can be found that the cascade with composited structure achieves better effect under different loads. In addition, the biggest advantage is that only using a group of PID parameters and a rough identification of the model, good control effect can be obtained.

5. **Conclusions.** A new control structure, named WDLCS is presented in the paper. This structure has the following advantages: 1) it has natural characters in reducing the influence of time delay and time-varying parameters; 2) both the software and the hardware can be used to reform the original control system, so it can protect the existing control structure's investment; 3) it can improve the control performance of original structure; 4) it can reduce the controller design complexity, because the controller can be



(a) Spray-water flow under 50% load (b) System output response under 50% load

Figure 9. Main steam temperature control effect under 50% load



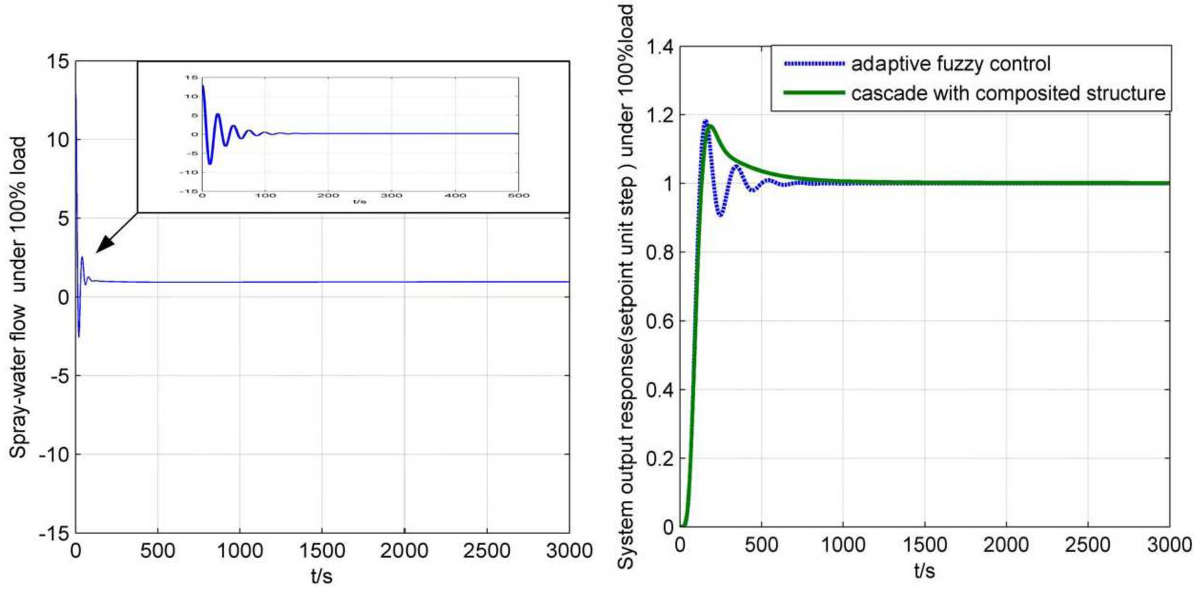
(a) Sprary-water flow under 75% load (b) System output response under 75% load

Figure 10. Main steam temperature control effect under 75% load

designed based on inexact plant model; 5) it can reduce the parameters tuning complexity, because it can improve the performance of original control system without parameters tuning.

The performance of anti-disturbance and reducing the influence of time delay is discussed. For control request of different sections, the dynamic weighted method of weighting factors selection is presented. A special composited structure with its rear-loop being Smith predictor is introduced in detail. The robustness of this composited structure is analyzed.

Through a lot of simulations, the WDLCS can obtain good control performance not only in the situation of plant with big time delay but also in the situation of plant with parameters time-varying and uncertainty.



(a) Spray-water flow under 100% load (b) System output response under 100% load

Figure 11. Main steam temperature control effect under 100% load

At last, the composite structure is used in the main stream control system. The control effect is compared with the adaptive fuzzy control. Through the comparison, it is proved that the structure has good performance to overcome high inertia, strong delay and time-variation without replacing the original controller or tuning the original control parameters.

REFERENCES

[1] P. H. Chang and J. W. Lee, A model reference observer for time-delay control and its application to robot trajectory control, *IEEE Trans. Control Systems Technology*, vol.4, pp.2-10, 1996.
[2] R. Raja, Q. Zhu, R. Samidurai, S. Senthilraj and W. Hu, Improved results on delay-dependent (H_∞) control for uncertain systems with time-varying delays, *Circuits Systems & Signal Processing*, vol.36, pp.1836-1859, 2017.
[3] X. Zhang, W. Lin and Y. Lin, Dynamic partial state feedback control of cascade systems with time-delay, *Automatica*, vol.77, pp.370-379, 2017.
[4] J. P. Richard, Time-delay systems: An overview of some recent advances and open problems, *Automatica*, vol.39, pp.1667-1694, 2003.
[5] K. J. Åström and B. Wittenmark, On self tuning regulators, *Automatica*, vol.9, pp.185-199, 1973.
[6] Z. Wang, L. Huang, Y. Zuo and L. Zhang, H_∞ control for uncertain system with time-delay and nonlinear external disturbance via adaptive control method, *International Journal of Control, Automation and Systems*, vol.8, pp.266-271, 2010.
[7] H. S. Jeong and C. W. Lee, Time delay control with state feedback for azimuth motion of the frictionless positioning device, *IEEE/ASME Trans. Mechatronics*, vol.2, pp.161-168, 1997.
[8] W. Zha, J. Zhai and S. Fei, Adaptive output feedback control for a class of uncertain stochastic nonlinear systems with unknown time-delays, *Asian Journal of Control*, vol.17, pp.2354-2362, 2015.
[9] Y. Niu, B. Chen and X. Wang, Sliding mode control for a class of nonlinear Itô stochastic systems with state and input delays, *International Journal of Control, Automation and Systems*, vol.7, pp.365-370, 2009.
[10] W. Chen and L. Zhang, Adaptive iterative learning control for nonlinearly parameterized systems with unknown time-varying delays, *International Journal of Control, Automation and Systems*, vol.8, pp.177-186, 2010.
[11] M. Darouach, Linear functional observers for systems with delays in state variables, *IEEE Trans. Automatic Control*, vol.46, pp.491-496, 2001.
[12] O. Sename, New trends in design of observers for time-delay systems, *Kybernetika -Praha-*, vol.37, pp.427-458, 2001.

[13] Y. M. Fu, G. R. Duan and S. M. Song, Design of unknown input observer for linear time-delay systems, *International Journal of Control, Automation, and Systems*, vol.2, pp.530-535, 2004.

[14] O. J. M. Smith, Closer control of loops with dead time, *Chemical Engineering Progress*, vol.53, pp.217-219, 1957.

[15] I. Kaya, IMC based automatic tuning method for PID controllers in a Smith predictor configuration, *Computers & Chemical Engineering*, vol.28, pp.281-290, 2004.

[16] K. J. Astrom, C. C. Hang and B. Lim, A new Smith predictor for controlling a process with an integrator and long dead-time, *IEEE Trans. Automatic Control*, vol.39, pp.343-345, 1994.

[17] Y.-D. Chen, P.-C. Tung and C.-C. Fuh, Modified Smith predictor scheme for periodic disturbance reduction in linear delay systems, *Journal of Process Control*, vol.17, pp.799-804, 2007.

[18] C. Hang, K. Lim and B. Chong, A dual-rate adaptive digital Smith predictor, *Automatica*, vol.25, pp.1-16, 1989.

[19] T. Hagglund, A predictive PI controller for processes with long dead times, *IEEE Control Systems Magazine*, vol.12, pp.57-60, 1992.

[20] X. L. Zhu, G. H. Yang, T. Li, C. Lin and L. Guo, LMI stability criterion with less variables for time-delay systems, *International Journal of Control, Automation and Systems*, vol.7, pp.530-535, 2009.

[21] Y. Fan, Z. Xu and L. Cheng, Study of adaptive fuzzy control of boiler superheated steam temperature based on dynamic mechanism analysis, *Proc. of Chinese Society of Electrical Engineering*, vol.17, pp.23-28, 1997.