Control of the Process with Inverse Response and Dead-time based on Disturbance Observer

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Abstract— **A modified disturbance observer based control scheme is proposed to control the processes with inverse response and dead-time. The two parts of proposed control scheme have explicit physical meanings: prefilter acts as a predictor of future control signal, and disturbance observer is used to reject the disturbance. It is a two degree-of-freedom control scheme. Two adjustable parameters are directly related to the performance of set-point response and disturbance rejection. Two disturbance observer design methods are proposed to reject step and ramp disturbances. Robustness of the closed-loop system is discussed. The proposed method is implemented on control software and applied on the dual-process simulator. Simulation and experimental results demonstrate the effectiveness of proposed method.**

I. Introduction

In chemical process industry, a number of processes exhibit inverse response behavior, such as drum boiler and distillation column [1]. When a step signal is applied to the inverse response processes, the processes will output in the opposite direction initially to the steady-state. The reason is that the process transfer function has odd number of right-half-plane (RHP) zeros. It is a challenge to control this kind of process. In the past literatures, many kinds of methods were used to control this kind of process, such as adaptive control methods [2-4], intelligent control methods [5], and classical methods based on linear time-invariant (LTI) model. Due to the complexity of previous two methods, classical methods were often used in distributed control system (DCS). There are two categories of control structures in classical methods to control the processes with inverse response. The first category of structure is PID controller with many kinds of tuning methods [6,7]. However, performance of PID control should be degraded to keep the stability margin. The second category of structure has an inverse response compensator [8-10]. However, dead-time is not considered in [8,9].

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The disturbance observer is an often-used control method in motion control field. It was originally presented by Ohnishi in 1987 [11]. Disturbance observer was used to estimate the disturbance and cancel the effect of the disturbances. In [12], a new load torque observer that takes the effects of system delay into consideration was proposed.

In this paper, we propose a modified disturbance observer to control the processes with inverse response and long dead-time. This paper is organized as follows. The original and modified control structure is introduced in section II. In section III, we illuminate the design principles of set-point controller and disturbance observer to reject the step disturbance and ramp disturbance. Robustness analysis is presented in section IV. The robust stable zone is given when there exist the uncertainties in the process gain, inverse response time constant, and dead-time. The control software is applied to control the dual-process simulator. The application results are shown in section V. Several remarkable conclusions are made in the last section.

II. Disturbance observer based control

In [12], the disturbance observer was used to compensate the unknown load torque, in which the delay of speed measurement was considered to enhance the robustness of the closed-loop system. Since the measurement delay is considered, the robustness and performance of speed control system is higher than that of original disturbance observer based speed control system. However, it has several drawbacks: the inverse function of delay-free part of process model is not proper, and it can not be used to observe the disturbance if it is applied to the process with inverse response because the RHP zeros of delay-free part will be the RHP poles and the disturbance observer will be unstable. We are inspired by the modification of load torque observer and present a new disturbance observer to control the process with inverse response and dead-time.

Assume that the transfer function of the process with inverse response and dead-time is represented by:

$$G(s) = G_{m0}(s)G_{inv}(s)e^{-\tau_m s} \tag{1}$$

where $G_{m0}(s)$ is the minimum-phase part of process, $G_{inv}(s)$ is the part with RHP zeros that satisfies the condition: $\lim_{s\to 0} G_{inv}(s)=1$, and $e^{-\tau_m s}$ is the delay part.

The significance of the load torque observer in [12] is to introduce delay part to the original disturbance observer. It can eliminate the delay part from the characteristic equation of closed-loop system in nominal case. As discussion on above, it can not be used directly to estimate the disturbance from input and output data of process with inverse response and dead-time. Then, we propose a modified disturbance observer to control the process with inverse response and dead-time.

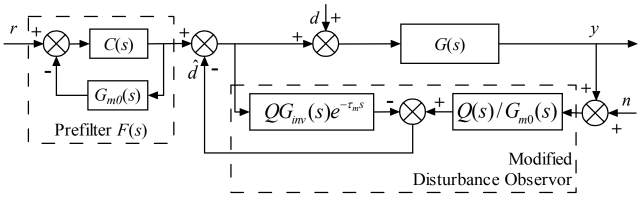

Fig. 1. New control scheme based on modified disturbance observer.

The proposed control scheme based on modified disturbance observer is shown on Fig. 1, where $C(s)$ is the set-point response controller, $G_{m0}(s)$ is the minimum-phase part of the process model, G_{inv} (s) is the part with RHP zeros, and $Q(s)$ is low-pass filter which steady-state gain is 1. $Q(s)$ is designed to trade off the robustness and disturbance rejection performance. Two modifications are proposed in the new disturbance observer. The first one is to multiply low-pass filter $Q(s)$ to the delay block and inverse model block. This modification can make $Q(s)/G_{m0}(s)$ proper provided that the relative degree of $Q(s)$ is high enough. The second one is that we introduce RHP zeros part, $G_{inv}(s)$, to disturbance observer to estimate the effect of inverse response. This modification eliminates the delay part and $G_{inv}(s)$ from the closed-loop characteristic equation. Under nominal case, the transfer functions from set-point r, disturbance d, and measurement noise n to output y are respectively:

$$G_{yr}(s)=\frac{C(s)G_{m0}(s)G_{inv}(s)}{1+C(s)G_{m0}(s)}e^{-\tau_m s} \tag{2}$$

$$G_{yd}(s)=G_{m0}(s)G_{inv}(s)e^{-\tau_m s}(1-Q(s)G_{inv}(s)e^{-\tau_m s}) \tag{3}$$

$$G_{yn}(s)=Q(s)G_{inv}(s)e^{-\tau_m s} \tag{4}$$

From above three equations, we can see that the set-point and disturbance response are decoupled. Using (2), we can design $C(s)$ to meet the desired set-point response. $Q(s)$ can be designed by (3) to obtain the satisfied disturbance rejection. In order to reject the disturbance and attenuate the measurement noise, $G_{yd}(s)$ should be zero at low frequency and $G_{yn}(s)$ should be zero at high frequency. A well-designed low-pass filter $Q(s)$ can be used to achieve this goal. The design principle of $Q(s)$ will be presented on section III.

The proposed control scheme is composed of two parts: prefilter part and disturbance rejection part. The prefilter part is composed of set-point response controller $C(s)$ and minimum part of process, which acts as a "set-point control signal predictor" because the signal that the $C(s)$ output according to the minimum-phase part of model effects the future process output. Disturbance rejection part is to estimate the disturbance, reject the disturbance, and guarantee the stability of the closed-loop system. The principle of modified disturbance observer is explained as follows. The set-point command r is handled by the prefilter and generate control signal. Then, the control signal is applied to the process and disturbance observer simultaneously. The process output will change after dead-time. The signal handled by $Q(s)G_{inv}(s)e^{-\tau_m s}$ part is same as the signal handled by $Q(s)/G_{m0}(s)$ part in nominal case. Thus, the disturbance observer output $\hat{d}$ is zero. If the disturbance is applied to process, the disturbance observer output $\hat{d}$ is:

$$\hat{d}=de^{-\tau_m s}G_{inv}(s)Q(s) \tag{5}$$

Since both the steady-state gains of $Q(s)$ and $G_{inv}(s)$ are one, $\hat{d}(\infty)=d$, which means the disturbance can be rejected.

In process control, the simplified model is often used to represent the actual process and tune the parameters of controller. The first order model and second order model are often used to represent the behavior of minimum-phase part. $(-T_{inv}s+1)$ is often used to approximate the inverse response part, in which T_{inv} is called inverse response time constant. Then, the models of process with inverse response and dead-time are given by following two forms:

$$G_1(s)=\frac{K_m}{T_m s+1}(-T_{inv}s+1)e^{-\tau_m s} \tag{6}$$

$$G_2(s)=\frac{K_m\omega_m^2}{s^2+2\xi_m\omega_m s+\omega_m^2}(-T_{inv}s+1)e^{-\tau_m s} \tag{7}$$

where K_m, T_m, τ_m, ξ_m, and ω_m are the process gain, time constant, dead-time, damped factor, and natural oscillation frequency, respectively.

III. TUNING PRINCIPLE

A. Tuning principle of set-point controller

The tuning principle of set-point response controller and disturbance observer is illuminated at this section. At first, the tuning principle of set-point controller is introduced. Undershoot is a well-known phenomenon if a step signal is applied to the process with inverse response and dead-time. Hence, undershoot should be considered when designing set-point controller $C(s)$. The desired set-point response is usually selected as the first-order dynamic. However, it is not a good choice to control the process with inverse response and dead-time. The reason is explained as follows.

If we set $C(s)G_{m0}(s)/(1+C(s)G_{m0}(s))$ to the first-order dynamic:

$$\frac{C(s)G_{m0}(s)}{1+C(s)G_{m0}(s)}=\frac{1}{\lambda s+1} \quad (8)$$

where λ is a adjustable parameter of the controller, which is directly related to set-point response. Then, in nominal case the transfer function from set-point r to output y becomes:

$$G_{yr}(s)=\frac{-T_{inv}s+1}{\lambda s+1}e^{-\tau_m s} \quad (9)$$

Suppose the magnitude of step input is R. According to initial value theorem, the magnitude of undershoot in proposed control scheme can be obtained by:

$$y_0=\lim_{s\to\infty}s\left(\frac{R}{s}\frac{-T_{inv}s+1}{\lambda s+1}\right)=-\frac{RT_{inv}}{\lambda} \quad (10)$$

In other words, the smaller λ is, the larger undershoot is.

If desired transfer function from set-point to process output is chosen as $G_{yr}(s)=\dfrac{-T_{inv}s+1}{a_1 s^2+a_0 s+1}e^{-\tau_m s}$, the initial undershoot will be zero when a step command applies to the control system. This choice is better than the above one. Certainly, undershoot as well as delay can not be eliminated from system because it is a natural property of such process.

According to above discussion, the tuning principle is to set $C(s)G_{m0}(s)/(1+C(s)G_{m0}(s))$ to the second-order dynamic:

$$\frac{C(s)G_{m0}(s)}{1+C(s)G_{m0}(s)}=\frac{1}{\lambda^2 s^2+2\xi\lambda s+1} \quad (11)$$

where λ is an adjustable parameter of the set-point controller, which is directly related to set-point response performance, and ξ is damped factor. λ and ξ are important factors for satisfactory behavior of a system. A small λ results in a fast system response but may cause large control effort. A small ξ can cause oscillatory dynamic. We suggest choosing ξ as 0.707. Then, only one parameter λ should be tuned by user to trade off the set-point response and undershoot. Then, the transfer function from set point r to output y becomes:

$$G_{yr}(s)=\frac{-T_{inv}s+1}{\lambda^2 s+2\xi\lambda s+1}e^{-\tau_m s} \quad (12)$$

The PI and PID controllers are often used to control the first-order and second-order processes. Assume that the practical PID controller has the following form:

$$C(s)=K_p\left(1+\frac{1}{T_i s}+T_d s\right)\frac{1}{T_F s+1} \quad (13)$$

The tuned parameters of $C(s)$ are shown in Table I when $G_{m0}(s)$ has the first-order and second-order dynamic respectively.

Table I
Tuned parameters for controller C(s)

$G_{m0}(s)$	K_p	T_i	T_d	T_F
$\frac{K_m}{T_m s+1}$	$\frac{T_m}{2\xi\lambda K_m}$	T_m	0	$\frac{1}{2\xi}$
$\frac{K_m\omega_m^2}{s^2+2\xi_m\omega_m s+\omega_m^2}$	$\frac{\xi_m}{\lambda\xi K_m\omega_m}$	$\frac{2\xi_m}{\omega_m}$	$\frac{1}{2\xi\omega_n}$	$\frac{1}{2\xi}$

If $G_{m0}(s)$ has a high-order dynamic, using PID controller can not achieve desired dynamics. Therefore, we directly tune prefilter part as:

$$F(s)=\frac{1}{G_{m0}(s)(\lambda^2 s+2\xi\lambda s+1)(\lambda s+1)^{d_0-2}} \quad d_0>2 \quad (14)$$

where d_0 is the relative degree of $G_{m0}(s)$ and is larger than 2. Hence, in nominal case the transfer function from set-point r to output y becomes:

$$G_{yr}(s)=\frac{-T_{inv}s+1}{(\lambda^2 s+2\xi\lambda s+1)(\lambda s+1)^{d_0-2}}e^{-\tau_m s} \quad (15)$$

B. Design of Q(s) to reject disturbance

The step disturbance ($d(s)=1/s$) and ramp disturbance ($d(s)=1/s^2$) are two kinds of disturbance that should be rejected in process control. The step disturbance and ramp disturbance are so-called Type I and Type II input disturbances, respectively. In order to reject Type I input disturbance, $Q(s)$ should meet the condition:

$$\lim_{s\to 0}(1-Q(s)G_{inv}(s)e^{-\tau_m s})=0 \quad (16)$$

If $Q(s)$ is designed to reject the Type II input disturbance, $Q(s)$ should meet (16) and the next condition:

$$\lim_{s\to 0}\frac{d}{ds}(1-Q(s)G_{inv}(s)e^{-\tau_m s})=0 \quad (17)$$

Simplifying (16) and (17) yields:

$$Q(0)G_{inv}(0)=1 \quad (18)$$

$$\lim_{s\to 0}\frac{d}{ds}(Q(s)G_{inv}(s))=\tau_m \quad (19)$$

Assume that the order of $G_{inv}(s)$ is d_{inv}. In order to make $Q(s)/G_{m0}(s)$ and $Q(s)G_{inv}(s)$ proper, the degree d_r of $Q(s)$ should not be smaller than maximum of d_{inv} and d_0. For rejecting step disturbance, one of the optional low-pass filters is:

$$Q(s)=\begin{cases}\dfrac{1}{\lambda_1^2 s^2+2\xi\lambda_1 s+1} & d_r\le 2\\[2ex] \dfrac{1}{(\lambda_1^2 s^2+2\xi\lambda_1 s+1)(\lambda_1 s+1)^{d_r-2}} & d_r>2\end{cases} \quad (20)$$

where λ_1 is an adjustable parameter which directly relates to the performance and robustness of the closed-loop system, d_{r} is the maximum of d_{inv} and d_0. The dumped factor ξ is usually chosen as 0.707. As for the ramp disturbance input, $Q(s)$ can be chosen by:

$$Q(s)=\begin{cases}\dfrac{\alpha s+1}{\lambda_1^2 s^2+2\xi\lambda_1 s+1} & d_r=1\\ \dfrac{\alpha s+1}{(\lambda_1^2 s^2+2\xi\lambda_1 s+1)(\lambda_1 s+1)^{d_r-1}} & d_r>1\end{cases} \tag{21}$$

Substituting (21) to (19) yields:

$$\alpha=\tau_m+2\xi\lambda_1+T_{inv}+(d_r-1)\lambda_1 \tag{22}$$

For the process which transfer function is (6), d_r equals 1. If the closed-loop system is designed to reject step disturbance, $Q(s)$ is chosen by $\frac{1}{\lambda_1^2 s^2+2\xi\lambda_1 s+1}$. If $Q(s)$ is set to $\frac{(2\xi\lambda_1+\tau_m+T_{inv})s+1}{\lambda_1^2 s^2+2\xi\lambda_1 s+1}$, the closed-loop system can reject step and ramp disturbance. For the process (7), d_r equals 2. If $Q(s)$ is set to $\frac{1}{\lambda_1^2 s^2+2\xi\lambda_1 s+1}$, the step disturbance can be rejected. If the closed-loop system is tuned to reject step and ramp disturbances, $Q(s)$ is $\frac{((2\xi+1)\lambda_1+\tau_m+T_{inv})s+1}{(\lambda_1^2 s^2+2\xi\lambda_1 s+1)(\lambda_1 s+1)}$. Increasing λ_1 yields the bad disturbance rejection performance and good robustness, while decreasing λ_1 yields the good disturbance rejection performance and bad robustness.

IV. ROBUST STABILITY ANALYSIS

There always exists uncertainty in practical process. According to small-gain theorem, the sufficient condition that guarantees the robust stability of closed-loop system is:

$$\|T(s)\|_\infty<1/\|\Delta(s)\|_\infty \tag{23}$$

where $T(s)$ is the complementary sensitive function of the nominal closed-loop system, $\Delta(s)$ is multiplicative uncertainty of process. The complementary sensitive function of proposed control scheme is given by:

$$T(s)=Q(s)G_{inv}(s)e^{-\tau_m s} \tag{24}$$

In this section, we discuss the stability of the closed-loop system where disturbance observer is designed to reject step disturbance. Then, the following form can be obtained:

$$\|T(s)\|_\infty=\left\|Q(s)G_{inv}(s)e^{-\tau_m s}\right\|_\infty=\left\|\frac{-T_{inv}s+1}{\lambda_1^2 s^2+2\xi\lambda_1 s+1}e^{-\tau_m s}\right\|_\infty \tag{25}$$

Three kinds of uncertainty (process gain uncertainty, inverse response time constant uncertainty, and dead-time uncertainty) are considered in this section. Firstly, the process gain uncertainty is considered. When the process gain is varied to $K_m+\Delta K$, the process gain uncertainty $\Delta(s)$ is $\Delta K/K_m$. If only the process gain uncertainty exists, the inequality (41) will be transformed to:

$$\sup_\omega\left|\frac{-T_{inv}j\omega+1}{1-\lambda_1^2\omega^2+2\xi\lambda_1 j\omega}e^{-j\tau_m\omega}\right|<\frac{K_m}{|\Delta K|} \tag{26}$$

Denote $\alpha=\lambda_1/T_{inv}$ and $\bar\omega=T_{inv}\omega$. Then, (26) will be transformed to:

$$\sup_{\bar\omega}\frac{|-j\bar\omega+1|}{|1-\alpha^2\bar\omega^2+j2\xi\alpha\bar\omega|}<\frac{K_m}{|\Delta K|} \tag{27}$$

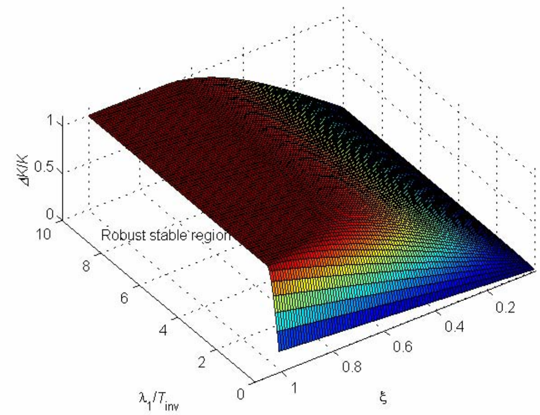

Fig. 2. Robust stable plane for gain uncertainty.

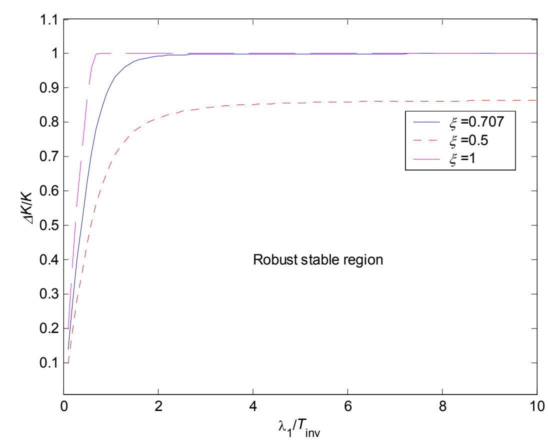

Fig. 3. Robust stable region for gain uncertainty when ξ is chosen as 0.5, 0.707, and 1.

It is easy to calculate the left part of (27). The robust stable boundary plane respected to α and ξ is shown on Fig.2. In order to show the robust stability boundary clearly, the robust stable boundaries where ξ =0.5, 0.707, and 1 are shown in Fig.3. If $\Delta K/K_m$ is lower than the robust stable plane, the closed-loop system is robust stable. It is concluded that decreasing λ_1/T_{inv} or ξ can reduce the closed-loop system tolerance for process gain variation.

Secondly, we consider the uncertainty in the inverse response time constant. Suppose that the inverse response time constant is perturbed from T_{inv} to $T_{inv}+\Delta T_{inv}$. The multiplicative uncertainty $\Delta(s)$ equals $\Delta T_{inv}s/(-T_{inv}s+1)$. Then the following theorem holds.

Theorem 1: For the process inverse response time constant uncertainty, $\Delta(s)=\Delta T_{inv}s/(-T_{inv}s+1)$, the closed-loop system is robust stable if

$$|\Delta T_{inv}| < 2\xi\lambda_1 \quad (28)$$

***Proof*:** Suppose the inverse response time constant varies from T_{inv} to $T_{\text{inv}}+\Delta T_{\text{inv}}$. The robust stability condition is transformed to:

$$\sup_{\omega}\left|\frac{-\Delta T_{inv} j\omega}{1-\lambda_1^2\omega^2+2\xi\lambda_1 j\omega}e^{-j\tau_m\omega}\right| < 1 \quad (29)$$

Denote $\alpha=\lambda_1/T_{inv}$, $\varpi=T_{inv}\omega$,and $\beta=|\Delta T_{inv}|/T_{inv}$. Equation (29) can be rewritten by:

$$\sup_{\varpi}\frac{|-\beta j\varpi|}{|1-\alpha^2\varpi^2+j2\xi\alpha\varpi|} < 1 . \quad (30)$$

Simplifying it yields $\beta < 2\xi\alpha$ when $\varpi = 1/\alpha$, i.e. $|\Delta T_{inv}| < 2\xi\lambda_1$. □

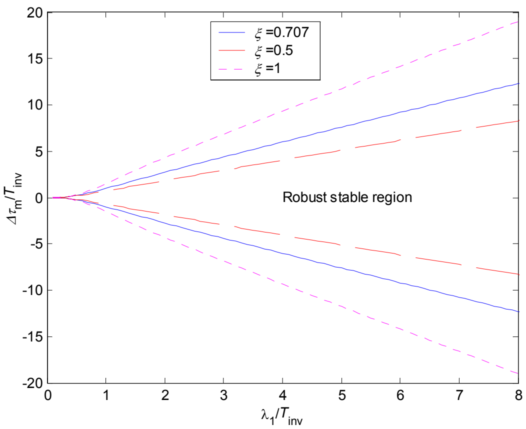

Fig. 4. Robust stable region for delay uncertainty when ξ is chosen as 0.5, 0.707, and 1.

Finally, dead-time uncertainties are considered. Suppose the dead-time is varied from τ_m to $\tau_m+\Delta\tau$. Then the multiplicative uncertainty $\Delta(s)$ of system is given by:

$$\Delta(s) = e^{-\Delta\tau s} - 1 \quad (31)$$

The sufficient condition that keeps the closed-loop system robust stability will be transformed to:

$$\sup_{\omega}\left|\frac{-\Delta T_{inv} j\omega+1}{1-\lambda_1^2\omega^2+2\xi\lambda_1 j\omega}e^{-j\tau_m\omega}(e^{-\Delta\tau j\omega}-1)\right| < 1 . \quad (32)$$

It can be rewritten by:

$$\sqrt{\frac{(-\omega T_{inv})^2+1}{(1-\lambda_1^2\omega^2)^2+4\xi^2\lambda_1^2\omega^2}} < \frac{1}{\sqrt{2-2\cos(\Delta\tau\omega)}} \quad \forall\omega \quad (33)$$

It is a nonlinear inequality and has no analytical solutions. The numerical solution for (33) can be solved by the following procedure. Rewrite (33) as

$$2-2\cos(\gamma\varpi) < \frac{(1-\alpha^2\varpi^2)^2+4\xi^2\alpha^2\varpi^2}{\varpi^2+1} \quad \forall\varpi \quad (34)$$

where $\gamma=\Delta\tau/T_{inv}$, $\alpha=\lambda_1/T_{inv}$, and $\varpi = T_{inv}\omega$. Denote

$$F_1 = 2-2\cos(\gamma\varpi)$$
$$F_2 = \frac{(1-\alpha^2\varpi^2)^2+4\xi^2\alpha^2\varpi^2}{\varpi^2+1} \quad (35)$$

The robustly stable boundary of (32) is the numerical solutions for the following two nonlinear equations:

$$F_1 = F_2$$
$$F_1' = F_2' \quad (36)$$

When ξ is selected to be 0.5, 0.707, and 1, the relationships between λ_1/T_{inv} and $\Delta\tau/T_{inv}$ are shown in Fig.4.

V. Simulation and Experimental Results

A. Control second-order process with inverse response and dead-time

Consider the following second-order process with inverse response and long dead-time:

$$G(s) = \frac{-2s+1}{2s^2+3s+1}e^{-5s} \quad (37)$$

Disturbance observer is designed to reject the step input disturbance. λ and λ_1 are all set to 2. Simulations are made under nominal case and model mismatch case. The simulation results under nominal case are shown on Fig.5. Three model mismatch conditions are considered: process gain varies from 1 to 1.3, inverse response time constant varies from 2 to 3, and dead-time varies from 5 to 6. The simulation results are shown on Fig.5. A step command is introduced at t=0 and a step disturbance is introduced at t=100. The magnitudes of disturbance and set-point input are 0.5 and 1, respectively.

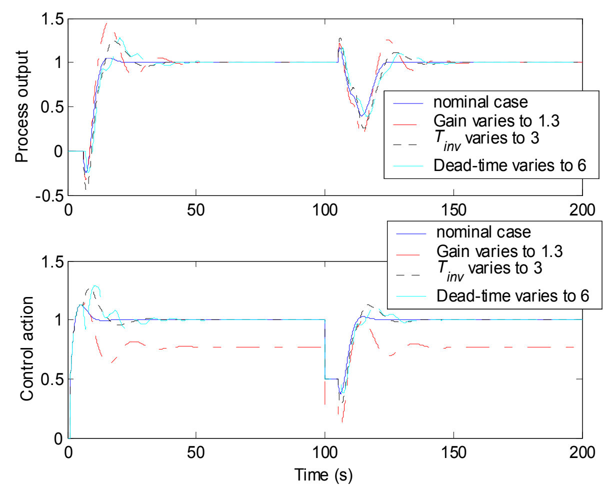

Fig. 5. Simulation results.

B. Application to dual process simulator

There is a dual-process simulator which type is KI-101 in advance process control laboratory of automation department. It is used to simulate the linear or nonlinear, low-order or high-order, stable or unstable, independent or coupled processes. In advance process control laboratory, it is used to verify the performance and robustness of the advanced process control algorithm. In our application, we configure it as a second-order process with inverse response and long dead-time. The proposed control method is implemented under Lab Window/CVI environment. An industrial PC installed analog-to-digital card and digital-to-analog cards acts as the advanced process controller. The picture of whole system is shown on Fig.6.

In order to tune the proposed controller, an open-loop experiment is applied to obtain the model of simulator. A direct identification method form step responses is used to obtain the model of simulator [13]. We obtain the model transfer function: $G(s) = \frac{-2.494\,s + 1}{25.11\,s^2 + 10.04\,s + 1.006} e^{-5.4s}$. The parameters of prefilter and disturbance observer, λ and λ1, are tuned to 2.494 and 4, respectively. Firstly, the controller is set to manual mode and manipulates process output to 20. Secondly, the operation mode is bumplessly transferred to automatic mode and set-point is set to 40 at 55s. When a new steady state is achieved, a step disturbance which magnitude is 20 is injected to the input of process at 105s. The control action and process output are shown on Fig.7.

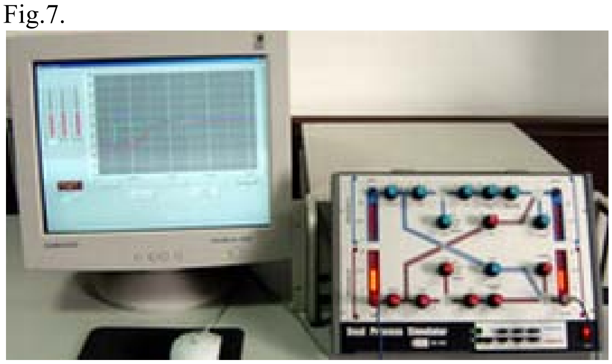

Fig. 6. Picture of whole system.

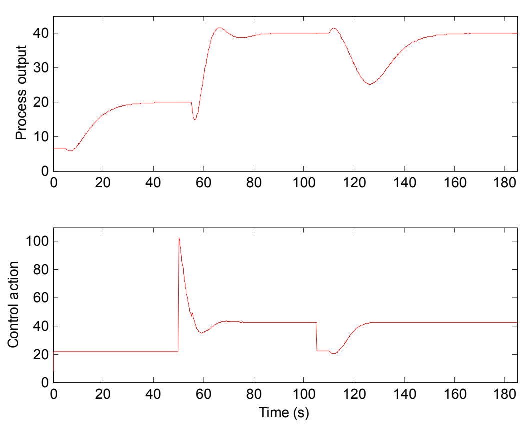

Fig. 7. Experimental result when λ and λ1 are tuned to 2.494 and 4.

VI. Conclusion

In this paper, a modified disturbance observer is proposed to control processes with inverse response and long dead-time. It is a two degree-of-freedom control scheme. The two parts of control scheme have explicit physical meaning: prefilter part acts as predictor of future control signal while disturbance observer acts as an estimator for disturbance to cancel the effect of disturbance. Step and ramp disturbance can be rejected by proposed control structure according to different design principles. Since there are only two adjustable parameters that are directly related to the setpoint response and disturbance response when the process model is obtained, it is easy to be tuned. The robust stability condition is given when there exist process gain uncertainty, inverse response time constants uncertainty, and dead-time uncertainty. The proposed control method is implemented to control the process simulator. Simulation and experimental results illuminate the effectiveness of proposed method. Although the proposed controller seems to be more complex than PID, the performance of proposed method is more enhanced. In fact, the implementation of the controller is easy. It is easy to transfer the high-order rational part, such as $Q(s)$, to state equation and solve it through the fourth-order Runge-Kutta integral algorithm.

References

[1] F.G. Shinskey, *Robust process control*. McGraw-Hill, New York, 1979.

[2] Meryem Makoudi and Larbi Radouane, "A robust model reference adaptive control for non-minimum phase systems with unknown or time-varying delay," *Automatica*, vol.36, pp.1057-1065, 2000.

[3] Youping Zhang and Zhong-Ping Jiang, "Direct pole placement adaptive tracking of non-minimum phase systems," *Systems & Control Letters*, vol.42, pp.55-67, 2001.

[4] Jing Yuan, "Improving an adaptive controller for non-minimum phase plants," *Automatica*, vol.38, pp.869–873, 2002.

[5] Abdelmoumene Toudeft and Partrick Gallinari, "Neural and adaptive controllers for a non-minimum phase varying time-delay system," *Artificial Intelligence in Engineering*, vol.11, pp.431-439, 1997.

[6] Huang Ying J. and Wang Yuan-Jay, "Robust PID controller design for non-minimum phase time delay systems," *ISA Trans.*, vol.40, pp.31-39, 2001.

[7] C. Pedret, R. Vilanova, R. Moreno, and I. Serra, "A refinement procedure for PID controller tuning," *Computers and Chemical Engineering*, vol.26, pp.903-908, 2002.

[8] Zhang Wei-Dong and Sun You-Xian, "Quantitative Control of Inverse Response process," *in Proc. of American Control Conference*, Albuquerque, New Mexico, 1997, pp.3257-3261.

[9] Linoya,K and R. J Altpeter, "Inverse Response In Process Control," *Ind. Eng. Chem.*, vol.54, pp.39-49, 1962.

[10] D. Manca, M. Rovaglio, and G. Pazzaglia, "Inverse Response Compensation and Control Optimization of Incineration Plants with Energy Production," *Computers and Chemical Engineering*, vol.22, pp.1879-1896, 1998.

[11] K. Ohnishi, "Microprocessor-controlled DC motor for load-insensitive position servo system," *IEEE Trans. On Industrial Electonics*, vol.34, pp.44-49, 1987.

[12] Kichul Hong and Kwanghee Nam, "A Load Torque Compensation Scheme Under the Speed Measurement Delay," *IEEE Trans. On Industrial Electronics*, vol.45, pp.283-290, 1998.

[13] Qing-guo Wang, Xin Guo, and Yong Zhang, "Direct identification of continuous time delay systems from step responses," *Journal of Process Control*, vol.11, pp.531-542, 2001.