A Two-Degree-of-Freedom PID-type Controller Incorporating the Smith Principle for Processes with Dead-Time

Qing-Chang Zhong*
Faculty of Electrical Engineering
Hunan Institute of Engineering
Xiangtan, Hunan, 411101
P. R. China

Han-Xiong Li
Dept. of MEEM
City University of Hong Kong
Hong Kong
P.R.China

Abstract

The Smith predictor is the most effective control scheme for processes with dead-time while the PID controller is the most widely used controller in industry. This paper presents a control scheme which combines their advantages. The proposed controller is inherently a PID-type controller in which the integral action is implemented using a delay unit rather than a pure integrator while retaining the advantage of the Smith predictor (Smith principle). The setpoint response and the disturbance response are decoupled from each other and can be designed separately. Another advantage of this control scheme is that the robustness is easy to analyze and can be guaranteed explicitly, compromising between the robustness and the disturbance response. Examples show that this controller is very effective in the control of processes with dead-time.

Key words: Dead-time compensator, process control, two-degree-of-freedom, PID control, Smith predictor

1 Introduction

Dead-time between input and output is a common phenomenon in industrial processes. It is also frequently used to compensate for model reduction where a high-order system, e.g. the thermal or curing process in integrated circuit (IC) packaging, is represented by a low-order model with delays. The presence of delay results in difficulties in both system analysis and controller design. The Smith predictor is a well-known control scheme for such processes and some modifications have been proposed to improve the system performance [1, 2]. The main advantage of the Smith predictor is the Smith principle [3]: the dead-time is eliminated from the characteristic equation of the closed-loop system. As a result, the main controller can be designed without consideration of the dead-time; moreover, the system analysis is simplified. However, the poor disturbance

*Dr. Qing-Chang Zhong, to whom correspondence should be addressed, is currently at Imperial College, London, UK. *Tel*: 44-20-759 46295, *Fax*: 44-20-759 46282, *Email*: zhongqc@ic.ac.uk, *URL*: http://come.to/zhongqc .

response and the difficulty in robustness analysis have limited the use of the Smith predictor, although some modified Smith predictors can improve the disturbance response [4, 1].

Nowadays, the most widely used controllers in industry are PID controllers [5, 6]. This is not only because of their simple structure and ease of use but also because of their good robustness and wide range of applicability. Many tuning methods [7, 8], including auto-tuning methods [5, 9], have been proposed to tune PID controllers. However, the uncertainty in a process is usually not explicitly considered when tuning a PID controller.

Motivated by the idea of time delay control [10, 11, 12] in which delay may be used to perform an integral action as well as a derivative action, this paper introduces a control scheme for processes with dead-time. The main characteristics of this control scheme are:

- It is a two-degree-of-freedom structure: the disturbance response and the setpoint response are decoupled from each other and can be designed separately;
- The Smith Principle is still valid: the dead-time is eliminated from the characteristic equation of the closed-loop system;
- The controller is easy to tune: only 2 or 3 parameters (in addition to the model parameters) need to be tuned; either 1 or 2 of them are determined by the desired setpoint response and another one is determined by compromising between disturbance response and robust stability;
- Robustness is easy to analyze graphically and is explicitly guaranteed;
- The feedback controller is inherently a PID controller;
- The integral action is implemented using a delay unit rather than a pure integrator as in common cases.

The rest of the paper is organized as follows: the control scheme is presented in Section 2 together with controller design; in Section 3 it is demonstrated that the feedback controller is inherently a PID controller; the robust stability is guaranteed in Section 4 compromising the disturbance response; examples are given in section 5 and Section 6 offers some conclusions.

2 Control Scheme

The proposed control scheme for processes with dead-time is shown in Figure 1. It consists of a pre-filter $F(s)$, a main controller $C(s)$ and a delay unit cascaded with a low-pass filter $Q(s)$. The pre-filter $F(s)$ is the first degree-of-freedom and the low-pass filter $Q(s)$ is the second degree-of-freedom. In this paper, we assume that $P(s)$ is a stable or critically stable minimum-phase model, which can cover the majority of the industrial (especially chemical) processes.

The positive feedback loop, containing $Q(s)e^{-\tau s}$, surrounded by a unity negative feedback, has been used in a repetitive control scheme [12, 13], in most cases, to control processes *without* dead time. Repetitive control is a technique using delay elements to improve some system performances, in particular, the tracking accuracy

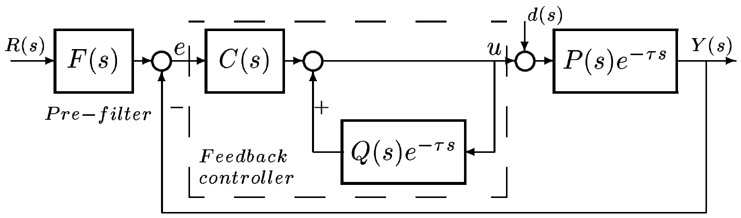


Figure 1: Two-degree-of-freedom controller for processes with dead-time

and/or the disturbance-rejection of periodic signals. With the learning ability of delay elements, repetitive control can reject/track any periodic signals of period τ. Hence, to some extent, the proposed control scheme is a kind of repetitive control for processes *with* dead-time. The delay element used here is equal to the dead time existing in the processes rather than the period of a periodic signal to be tracked or rejected. Obviously, a by-product of this control scheme is that if the bandwidth of $Q(s)$ is wide enough, it can track/reject periodic signals of which the period is equal to the dead-time.

The transfer function from setpoint $R(s)$ to output $Y(s)$ is

$$\begin{aligned} G_r(s) &= F(s)\frac{C(s)\frac{1}{1-Q(s)e^{-\tau s}}P(s)e^{-\tau s}}{1+C(s)\frac{1}{1-Q(s)e^{-\tau s}}P(s)e^{-\tau s}} \\ &= F(s)\frac{C(s)P(s)e^{-\tau s}}{1-Q(s)e^{-\tau s}+C(s)P(s)e^{-\tau s}}. \end{aligned} \tag{1}$$

If the main controller $C(s)$ is designed (in the nominal case) as

$$C(s) = Q(s)P^{-1}(s), \tag{2}$$

then

$$G_r(s) = F(s)Q(s)e^{-\tau s}. \tag{3}$$

If the pre-filter $F(s)$ is designed as

$$F(s) = \frac{1}{\lambda s+1}Q^{-1}(s) \tag{4}$$

or

$$F(s) = \frac{1}{\lambda^2 s^2 + 2\lambda\zeta s + 1}Q^{-1}(s), \tag{5}$$

then the desired setpoint response is obtained as

$$G_r(s) = \frac{1}{\lambda s+1}e^{-\tau s} \quad \text{or} \quad G_r(s) = \frac{1}{\lambda^2 s^2 + 2\lambda\zeta s + 1}e^{-\tau s} \quad (\lambda > 0, \zeta > 0), \tag{6}$$

which is independent of the second degree-of-freedom $Q(s)$. The disturbance response is

$$G_d(s) = \frac{P(s)e^{-\tau s}}{1+C(s)\frac{1}{1-Q(s)e^{-\tau s}}P(s)e^{-\tau s}}$$

$$= (1 - Q(s)e^{-\tau s})P(s)e^{-\tau s}, \tag{7}$$

which is independent of the first degree-of-freedom $F(s)$. Therefore, the setpoint response and the disturbance response are decoupled from each other and can be designed separately.

In order to obtain zero static error under step setpoint/disturbance change, $Q(s)$ should satisfy

$$Q(0) = 1 \tag{8}$$

for processes without an integrator, and furthermore,

$$\dot{Q}(0) = \tau \tag{9}$$

for processes with an integrator. In order to implement the controller physically, the relative degree of $Q(s)$ should not be less than that of $P(s)$ and the relative degree of the delay-free part of the desired response should not be less than that of $Q(s)$. Hence, in general, $Q(s)$ is a low-pass filter with a static gain of 1. In order to guarantee the stability of $Q^{-1}(s)$ and the internal stability of the closed-loop system, $Q(s)$ should be minimum-phase.

Many of the industrial processes $G(s) = P(s)e^{-\tau s}$ can be modeled as a first-order plus dead-time (FOPDT) or a second-order plus dead-time (SOPDT), where

$$P(s) = \frac{K}{Ts+1} \quad \text{or} \quad P(s) = \frac{K}{T^2s^2 + 2\mu Ts + 1}. \tag{10}$$

For these processes, the proposed controllers are given in Table 1.

For another kind of typical industrial processes, integrating processes with dead-time (IPDT) $G(s) = \frac{K}{s}e^{-\tau s}$, the minimum order of $Q(s)$ should be 2 because of the constraint (9). Let

$$Q(s) = \frac{\beta s + 1}{(\alpha s + 1)^2}, \tag{11}$$

then, according to (9),

$$\beta = 2\alpha + \tau. \tag{12}$$

The corresponding controllers needed to obtain a desired first-order or second-order response plus dead-time (6) are also given in Table 1.

3 Essence of the controller

This Section is to demonstrate that the proposed feedback controller is inherently a PID controller.

(1) FOPDT

In this case, according to Table 1, the feedback controller is

$$
\begin{aligned}
C(s)\frac{1}{1-Q(s)e^{-\tau s}} &= \frac{Ts+1}{K(\alpha s+1)}\frac{1}{1-\frac{1}{\alpha s+1}e^{-\tau s}} \\
&= \frac{Ts+1}{K}\frac{1}{\alpha s+1-e^{-\tau s}} \\
&\approx \frac{Ts+1}{K(\alpha+\tau)s},
\end{aligned}
\tag{13}
$$

which means it is inherently a PI controller $K_p + \frac{K_i}{s}$ with

$$
\begin{cases}
K_p = \frac{T}{K(\alpha+\tau)}, \\
K_i = \frac{1}{K(\alpha+\tau)}.
\end{cases}
\tag{14}
$$

(2) SOPDT

In this case, according to Table 1, the feedback controller is

$$
\begin{aligned}
C(s)\frac{1}{1-Q(s)e^{-\tau s}} &= \frac{T^2s^2+2\mu Ts+1}{K(\alpha s+1)^2}\frac{1}{1-\frac{1}{(\alpha s+1)^2}e^{-\tau s}} \\
&= \frac{1}{K}\frac{T^2s^2+2\mu Ts+1}{(\alpha s+1)^2-e^{-\tau s}} \\
&\approx \frac{T^2s^2+2\mu Ts+1}{K(\alpha^2 s+2\alpha+\tau)s}.
\end{aligned}
\tag{15}
$$

This can be re-formulated as a PID controller $K_p + \frac{K_i}{s} + \frac{K_d s}{\tau_d s+1}$ with

$$
\begin{cases}
K_p = \frac{2\mu T(2\alpha+\tau)-\alpha^2}{K(2\alpha+\tau)^2}, \\
K_i = \frac{1}{K(2\alpha+\tau)}, \\
K_d = \frac{T^2}{K(2\alpha+\tau)} - \frac{2\mu T\alpha^2(2\alpha+\tau)-\alpha^4}{K(2\alpha+\tau)^3}, \\
\tau_d = \frac{\alpha^2}{2\alpha+\tau}.
\end{cases}
\tag{16}
$$

(3) IPDT

In this case, according to Table 1, the feedback controller is

$$
\begin{aligned}
C(s)\frac{1}{1-Q(s)e^{-\tau s}} &= \frac{(2\alpha+\tau)s^2+s}{K(\alpha s+1)^2}\frac{1}{1-\frac{(2\alpha+\tau)s+1}{(\alpha s+1)^2}e^{-\tau s}} \\
&= \frac{1}{K}\frac{(2\alpha+\tau)s^2+s}{(\alpha s+1)^2-(2\alpha+\tau)se^{-\tau s}-e^{-\tau s}} \\
&= \frac{1}{K}\frac{(2\alpha+\tau)s+1}{\alpha^2 s-\tau+(2\alpha+\tau)(1-e^{-\tau s})+\frac{1-e^{-\tau s}}{s}} \\
&= \frac{1}{K}\frac{(2\alpha+\tau)s+1}{\alpha^2 s-\tau+((2\alpha+\tau)s+1)\frac{1-e^{-\tau s}}{s}} \\
&\approx \frac{1}{K}\frac{(2\alpha+\tau)s+1}{\alpha^2 s+(2\alpha+\tau)\tau s}
\end{aligned}
\tag{17}
$$

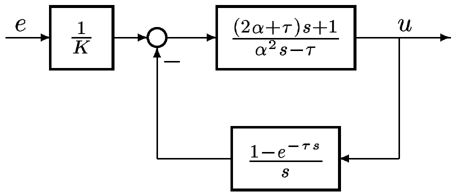


Figure 2: Equivalent feedback controller for IPDT

$$= \frac{(2\alpha+\tau)s+1}{K(\alpha+\tau)^2 s},$$

which means, again, that the feedback controller is inherently a PI controller $K_p + \frac{K_i}{s}$ with

$$\begin{cases} K_p = \frac{2\alpha+\tau}{K(\alpha+\tau)^2}, \\ K_i = \frac{1}{K(\alpha+\tau)^2}. \end{cases} \tag{18}$$

Hence, the proposed controller retains the advantages of the Smith predictor and the advantages of the PID controller. A prominent advantage of the tuning formulae (14), (16) and (18) is that there exists a free parameter α. This free parameter can be used to compromise between the disturbance response and the robustness (as shown later in Section 5); it can also be used to optimize a certain performance index, e.g. gain or phase margin. These tuning formulae for a PID controller (obtained under the approximation $e^{-\tau s} \approx 1-\tau s$) are only used here to show that the proposed controller is inherently a PID-type controller; more accurate tuning formulae for a PID controller can be obtained using the Padé approximation.

It is worth noting that according to (17), the feedback controller for IPDT can be rewritten as

$$C(s)\frac{1}{1-Q(s)e^{-\tau s}} = \frac{1}{K}\frac{\frac{(2\alpha+\tau)s+1}{\alpha^2 s-\tau}}{1+\frac{(2\alpha+\tau)s+1}{\alpha^2 s-\tau}\frac{1-e^{-\tau s}}{s}}. \tag{19}$$

This is a negative feedback loop of $\frac{(2\alpha+\tau)s+1}{\alpha^2 s-\tau}$ through a finite impulse response (FIR) block $\frac{1-e^{-\tau s}}{s}$ cascaded by a gain $\frac{1}{K}$, as shown in Figure 2. This feedback controller itself is stable if $\alpha > 0.63\tau$ [14].

4 Robustness Analysis

In the nominal case, the loop transfer function of the control system shown in Figure 1 is

$$L(s) = \frac{Q(s)e^{-\tau s}}{1-Q(s)e^{-\tau s}}. \tag{20}$$

Hence, the corresponding sensitivity function is

$$S(s) = \frac{1}{1+L(s)} = 1-Q(s)e^{-\tau s} \tag{21}$$

and the complementary sensitivity function is

$$T(s) = 1 - S(s) = Q(s)e^{-\tau s}. \quad (22)$$

This means that $Q(s)$ does not only affect the disturbance response (7) but also affects the robust stability and the robust performances. It should be determined by compromising between the disturbance response and the robustness.

Theorem 1 Assume that there exists a multiplicative uncertainty $\Delta(s) \in H_\infty$ in the delay-free part, then the closed-loop system is robustly stable if $\|Q(s)\|_\infty < \frac{1}{\|\Delta(s)\|_\infty}$.

Proof: Since

$$\begin{aligned} \|T(s)\Delta(s)\|_\infty &= \left\|Q(s)e^{-\tau s}\Delta(s)\right\|_\infty \\ &= \|Q(s)\Delta(s)\|_\infty \\ &< \|Q(s)\|_\infty \cdot \|\Delta(s)\|_\infty \\ &< 1, \end{aligned}$$

according to the Theorem 8.5 in [15], the closed-loop system is internally stable for all $\Delta(s) \in H_\infty$ if $\|Q(s)\|_\infty < \frac{1}{\|\Delta(s)\|_\infty}$.

Remarks:

1. There is no bound limit on the multiplicative uncertainty $\Delta(s)$ provided that it is stable.

2. If the magnitude frequency response of $Q(s)$ stays under that of $\frac{1}{\Delta(s)}$ then the system is robustly stable. $Q(s)$ can be designed graphically, as shown in Section 5.

3. If the uncertainty has a norm bound of less than 1, then almost every low-pass filter which meets the condition (8) guarantees the robust stability of the system. It can be designed by considering the disturbance response alone.

If there exists an uncertainty τ_Δ in dead-time, then

$$\begin{aligned} G(s) &= P(s)e^{-(\tau+\tau_\Delta)s} \\ &\doteq P(s)(1+\Delta(s))e^{-\tau s}, \end{aligned} \quad (23)$$

and the dead time uncertainty can be converted to a multiplicative uncertainty

$$\Delta(s) = e^{-\tau_\Delta s} - 1. \quad (24)$$

Hence, the following results hold:

Corollary 1 Assume that there exists uncertainty $\tau_\Delta > -\tau$ in dead-time, then the closed-loop system is robustly stable if $\|Q(s)\|_\infty < \frac{1}{\left\|e^{-\tau_\Delta s}-1\right\|_\infty}$.

Remark: For dead-time uncertainty τ_Δ, a recommendation of α is about $\alpha = (1 \sim 1.4)\tau_\Delta$ when $Q(s)$ is chosen as a first-order low pass filter.

Corollary 2 Assume that there exist an uncertainty $\tau_\Delta > -\tau$ in dead-time and a multiplicative uncertainty $\Delta(s) \in H_\infty$ in the delay-free part, then the closed-loop system is robustly stable if $\|Q(s)\|_\infty < \frac{1}{\|(1+\Delta(s))e^{-\tau_\Delta s}-1\|_\infty}$.

5 Examples

5.1 Example 1: FOPDT

Consider a widely studied process [7, 16]

$$G(s) = P(s)e^{-\theta s} = \frac{e^{-0.5s}}{s+1}. \tag{25}$$

A PI controller was tuned as $C(s) = 1.05(1+\frac{1}{s})$ in [7] to obtain a phase margin of $60°$ and a gain margin of 3. The resulting settling time was about 2.3sec. Here we choose $\lambda = 0.3$sec to obtain a desired settling time of about 1.4sec. If there is no uncertainty, $Q(s) = \frac{1}{\alpha s+1}$ can be chosen as having a bandwidth broad enough to obtain the desired disturbance response. The responses with $\alpha = 0.01$, $\alpha = 0.1$ and $\alpha = 0.4$ are shown in Figure 3(a) and are compared to those of Ho *et al.* (noted as Ho *et al.* in Figures). A step disturbance $d = -0.4$ acts at $t = 5$sec. When $\alpha = 0.4$ the disturbance response is similar to that of Ho *et al.* For $\alpha < 0.4$ the disturbance response is better than that of Ho *et al.* If there exists a dead-time uncertainty $\tau_\Delta = 0.1$sec, the response under $\alpha = 0.4$ is shown in Figure 3(b). As can be seen, the proposed controller achieves a much better performance.

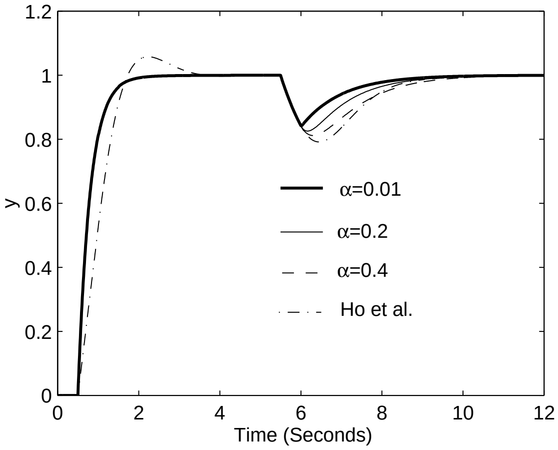
The proposed control scheme has the potential to compromise between the disturbance response and the robust stability, in addition to decoupling the setpoint response and the disturbance response. For a dead-time uncertainty $\tau_\Delta = 1.0$sec, the PI controller $C(s) = 1.05(1+\frac{1}{s})$ critically destabilizes the system, but it is possible to obtain a stable system for $Q(s)$ with $\alpha > 0.7$, as shown in Figure 3(c). An appropriate value is $\alpha = 1.2$, with which the response is shown in Figure 3(d).

5.2 Example 2: SOPDT

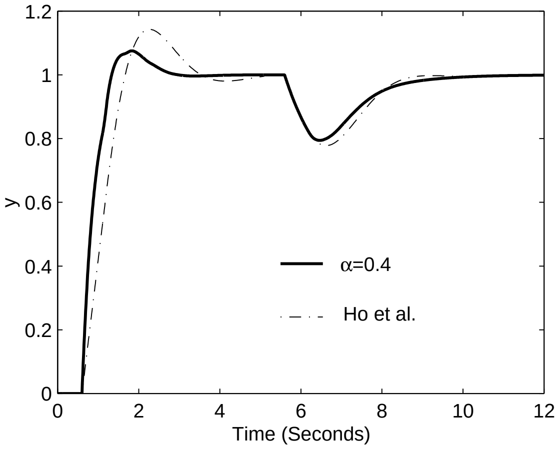
Consider the SOPDT model

$$G(s) = \frac{e^{-30s}}{(10s+1)^2} \tag{26}$$

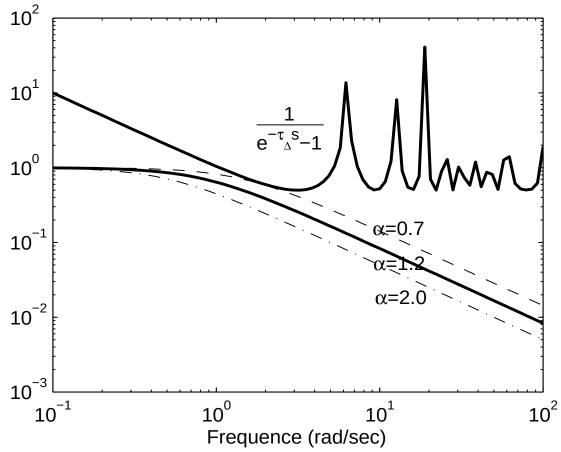
studied in [17]. A PID controller was tuned as $0.662(1+\frac{1}{29.11s}+9.036s)$ in [17], and the resulting settling time was about 120sec. Here, the responses with $\alpha = 0.1$, $\alpha = 2$ and $a = 5$ and with $\lambda = 7, \zeta = 1$ are shown in Figure 4(a) and are compared to those of Lee *et al.* A step change $d = -0.4$ acts at $t = 120$sec. The smaller the α, the better the disturbance response.



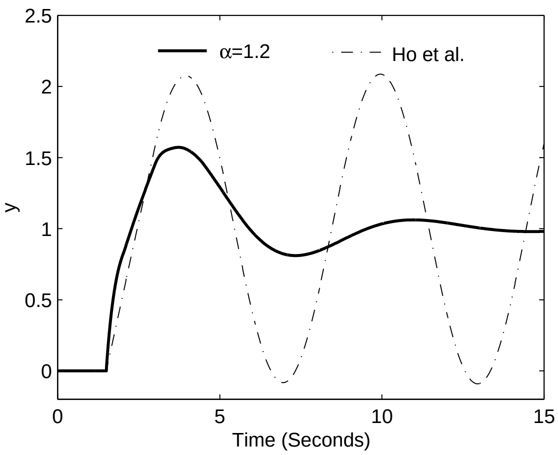
(a) Responses of the nominal case



(b) Responses when $\tau_\Delta = 0.1$sec



(c) Design of $Q(s)$ for $\tau_\Delta = 1.0$sec



(d) Responses when $\tau_\Delta = 1.0$sec

Figure 3: Example 1

Assume that there exists a multiplicative uncertainty $\Delta(s)$ in the delay-free part, of which the worst case is $\Delta(s) = \frac{1}{(s+1)(0.5s+1)} - 1 = \frac{s(0.5s+1.5)}{0.5s^2+1.5s+1}$. In order to design $Q(s) = \frac{1}{(\alpha s+1)^2}$ the magnitude frequency response of $\frac{1}{\Delta(s)}$ is shown in Figure 4(b). The frequency responses of three candidates of $Q(s)$ with $\alpha = 0.5$, $\alpha = 1.5$ and $a = 5$ are also shown in Figure 4(b). The corresponding responses are obtained as shown in Figure 4(c). Clearly, the proposed controller achieves much better performances.

5.3 Example 3: IPDT

Consider a widely studied integrating process with dead-time [4, 18, 19]

$$G(s) = \frac{1}{s}e^{-5s}. \tag{27}$$

and assume there exists a dead-time uncertainty $0 \leq \tau_\Delta \leq 0.5\,\text{sec}$.

Here, $Q(s) = \frac{(2\alpha+5)s+1}{(\alpha s+1)^2}$ is selected with $\alpha = 2.1$, $\alpha = 4$ and $\alpha = 8$ as shown in Figure 5(a). The desired setpoint response is designed with $\lambda = 2$. The responses in the nominal condition are shown in Figure 5(b); the responses when $\tau_\Delta = 0.5\,\text{sec}$ are shown in Figure 5(c). In all cases, a step disturbance $d(t) = 0.1$ acts at $t = 15sec$. The smaller the α, the better the disturbance response but the worse the robust performance. The larger the α, the better the robust performance but the worse the disturbance response.

6 Conclusions

A control scheme combining the advantages of a PID controller and a Smith predictor is presented in this paper. It is a two-degree-of-freedom structure with the ability to decouple the setpoint response and disturbance response from each other. The dead-time is eliminated from the characteristic equation of the closed-loop system and only 2 or 3 parameters (in addition to model parameters) need to be tuned; either 1 or 2 of them (belonging to the degree-of-freedom $F(s)$) are determined by the desired response and another one (belonging to the degree-of-freedom $Q(s)$) is determined by compromising between robustness and disturbance response. Examples show that the proposed method is very effective to control processes with dead-time and results in a wider range of applicability.

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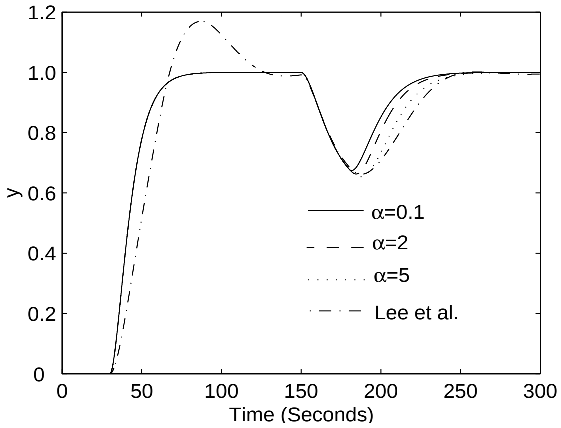
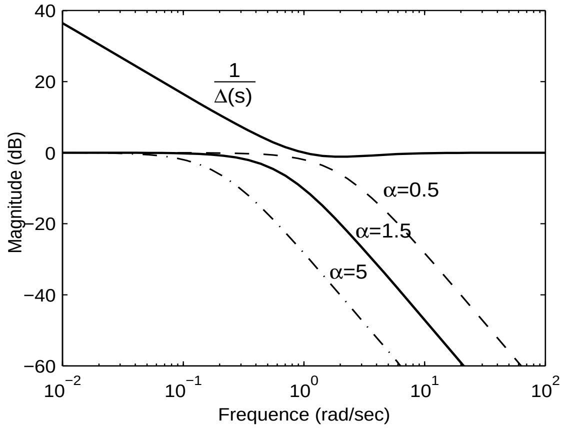
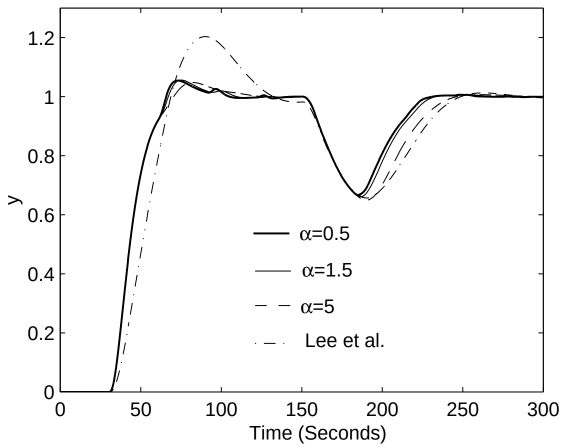


(a) Nominal responses

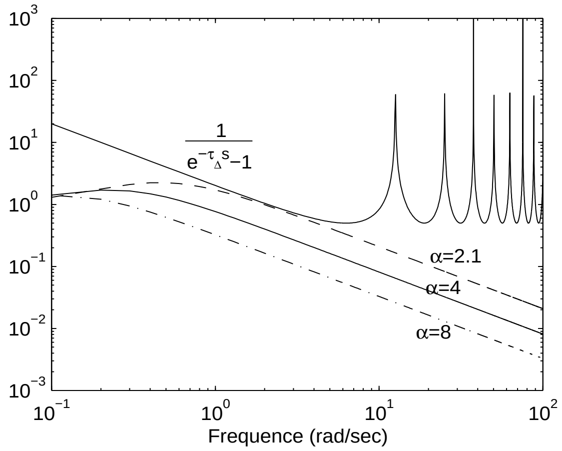


(b) Design of $Q(s)$ for $\Delta(s) = \frac{s(0.5s+1.5)}{0.5s^2+1.5s+1}$

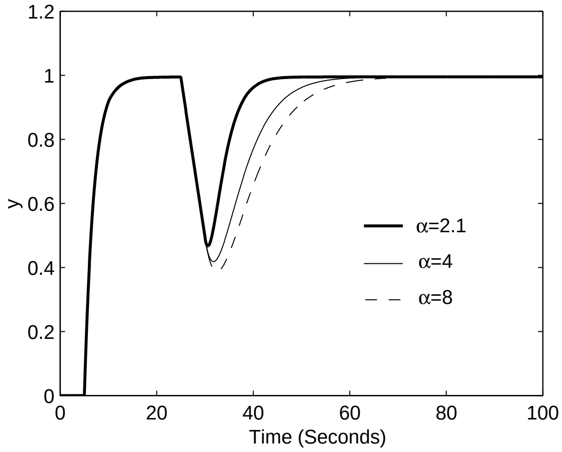


(c) Responses under $\Delta(s) = \frac{s(0.5s+1.5)}{0.5s^2+1.5s+1}$

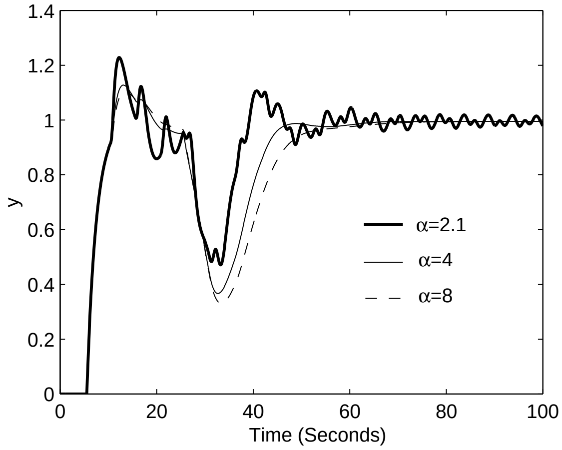
Figure 4: Example 2



(a) Design of $Q(s)$



(b) Responses when $\tau_\Delta = 0$



(c) Responses when $\tau_\Delta = 0.5\,\mathrm{sec}$

Figure 5: Example 3

Table 1: Controllers for Typical Processes with Dead-time ($\alpha > 0$)

	$P(s)$	$Q(s)$	$C(s)$	$F(s)$	Desired Response
FOPDT	$\frac{K}{Ts+1}$	$\frac{1}{\alpha s+1}$	$\frac{Ts+1}{K(\alpha s+1)}$	$\frac{\alpha s+1}{\lambda s+1}$	$\frac{1}{\lambda s+1}e^{-\tau s}$
SOPDT	$\frac{K}{T^2s^2+2\mu Ts+1}$	$\frac{1}{(\alpha s+1)^2}$	$\frac{T^2s^2+2\mu Ts+1}{K(\alpha s+1)^2}$	$\frac{(\alpha s+1)^2}{\lambda^2s^2+2\lambda\zeta s+1}$	$\frac{1}{\lambda^2s^2+2\lambda\zeta s+1}e^{-\tau s}$
IPDT*	$\frac{K}{s}$	$\frac{(2\alpha+\tau)s+1}{(\alpha s+1)^2}$	$\frac{(2\alpha+\tau)s^2+s}{K(\alpha s+1)^2}$	$\frac{(\alpha s+1)^2}{(\lambda s+1)((2\alpha+\tau)s+1)}$	$\frac{1}{\lambda s+1}e^{-\tau s}$
				$\frac{(\alpha s+1)^2}{(\lambda^2s^2+2\lambda\zeta s+1)((2\alpha+\tau)s+1)}$	$\frac{1}{\lambda^2s^2+2\lambda\zeta s+1}e^{-\tau s}$

*Note: In this case, the controller cannot be implemented as the structure shown in Figure 1 because it is no longer internally stable. An equivalent way is to implement the feedback controller $C(s)\frac{1}{1-Q(s)e^{-\tau s}}$ as the structure shown in Figure 2 where the FIR block $\frac{1-e^{-\tau s}}{s}$ should be implemented non-dynamically [1].

List of Figures

References

[1] Palmor, Z. J. Time-delay compensation — Smith predictor and its modifications. In *The Control Handbook*; Levine, S. Eds; pages 224–237; CRC Press, 1996.

[2] Majhi, S.; Atherton, D.P. Modified Smith predictor and controller for processes with time delay. *IEE Proc.-Control Theory Appl.* **1999**, 146(5), 359–366.

[3] Åström, K. J.; Wittenmark, B. *Computer-Controlled Systems: Theory and Design*; Prentice-Hall: Englewood Cliffs, NJ, 1984.

[4] Åström, K.J.; Hang, C.C.; Lim, B.C. A new Smith predictor for controlling a process with an integrator and long dead-time. *IEEE Trans. Automat. Control*. **1994**, 39, 343–345.

[5] Åström, K.J.; Hagglund, T. *Automatic Tuning of PID Controllers*; Instrument Society of America, 1988.

[6] Åström, K.J.; Hagglund, T. *PID Controllers: Theory, Design, and Tuning*; Instrument Society of America, 2nd edition, 1995.

[7] Ho, W.K.; Hang, C.C.; Cao, L.S. Tuning of PID controllers based on gain and phase margin specifications. *Automatica*. **1995**, 31(3), 497–502.

[8] Ho, W.K.; Xu, W. PID tuning for unstable processes based on gain and phase-margin specifications. *IEE Proc.-Control Theory Appl.* **1998**, 145(5), 392–396.

[9] Majhi, S.; Atherton, D.P. Autotuning and controller design for processes with small time delays. *IEE Proc.-Control Theory Appl.* **1999**, 146(5), 415–425.

[10] Zhong, Q.C. Time Delay Control & Its Applications. Ph.D. Dissertation, Shanghai Jiao Tong University, Shanghai, China, Dec. 1999.

[11] Youcef-Toumi, K.; Ito, O. A time delay controller for systems with unknown dynamics. *Journal of Dyn. Sys. Meas. Con. -Trans. ASME*. **1990**, 112(1), 133–142.

[12] Hara, S.; Yamamoto, Y.; Omata, T.; Nakano, M. Repetitive control system: A new type servo system for periodic exogenous signals. *IEEE Trans. Automat. Control*. **1988**, 33, 659–668.

[13] Weiss, G.; Hafele, M. Repetitive control of MIMO systems using H_∞ design. *Automatica*. **1999**, 35(7), 1185–1199.

[14] Mirkin, L.; Zhong, Q.C. Coprime parametrization of 2DOF controller to obtain sub-ideal disturbance response for processes with dead time. In *Proc. of the 40th IEEE Conf. on Decision & Control*, pages 2253–2258, Orlando, USA, December, 2001.

[15] Zhou, K. *Essentials of Robust Control*; Prentice-Hall: Upper Saddle River, N.J., 1998.

[16] Zhong, Q.C.; Xie, J.Y.; Jia, Q. Time delay filter-based deadbeat control of process with dead time. *Industrial & Engineering Chemistry Research*. **2000**, 39(6), 2024–2028.

[17] Lee, Y. H.; Park, S. W.; Lee, M. Y.; Brosilow, C. PID controller tuning for desired closed-loop responses for SI/SO systems. *AIChE Journal*. **1998**, 44(1), 106–115.

[18] Matausek, M.R.; Micic, A.D. On the modified Smith predictor for controlling a process with an integrator and long dead-time. *IEEE Trans. Automat. Control*. **1999**, 44(8), 1603–1606.

[19] Normey-Rico, J.E.; Camacho, E.F. Robust tuning of dead-time compensators for process with an integrator and long dead-time. *IEEE Trans. Automat. Control*. **1999**, 44(8), 1597–1603.