

2-Degree-of-Freedom Proportional–Integral–Derivative-Type Controller Incorporating the Smith Principle for Processes with Dead Time

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The Smith predictor is the most effective control scheme for processes with dead time while the proportional–integral–derivative (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.

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 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 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.^{1,4}

Nowadays, the most widely used controllers in industry are proportional–integral–derivative (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 autotuning 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.

Because we were motivated by the idea of time delay control,^{10–12} 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 as follows:

(i) It is a 2-degree-of-freedom structure: the disturbance response and the setpoint response are decoupled from each other and can be designed separately.

(ii) The Smith principle is still valid: the dead time is eliminated from the characteristic equation of the closed-loop system.

(iii) The controller is easy to tune: only two or three parameters (in addition to the model parameters) need to be tuned; either one or two of them are determined by the desired setpoint response, and another one is determined by compromising between disturbance response and robust stability.

(iv) Robustness is easy to analyze graphically and is explicitly guaranteed.

(v) The feedback controller is inherently a PID controller.

(vi) 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 prefilter $F(s)$, a main controller $C(s)$, and a delay unit cascaded with a low-pass filter $Q(s)$. The prefilter $F(s)$ 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.

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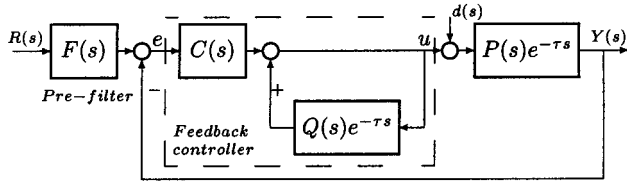


Figure 1. 2-degree-of-freedom controller for processes with dead time.

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 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. Hence, a byproduct 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

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

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

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

then

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

If the prefilter $F(s)$ is designed as

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

or

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

then the desired setpoint response is obtained as

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

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

$$G_d(s) = \frac{P(s) e^{-\tau s}}{1 + C(s) \frac{1}{1 - Q(s) e^{-\tau s}} P(s) e^{-\tau s}} = (1 - Q(s) e^{-\tau s}) P(s) e^{-\tau s} \quad (7)$$

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.

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

$$Q(0) = 1 \quad (8)$$

for processes without an integrator and, furthermore,

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

for processes with an integrator. 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. 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

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

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

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

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

then, according to eq 9,

$$\beta = 2\alpha + \tau \quad (12)$$

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

3. Essence of the Controller

This section demonstrates that the proposed feedback controller is inherently a PID controller.

(1) FOPDT. In this case, according to Table 1, the feedback controller is

$$C(s) \frac{1}{1 - Q(s) e^{-\tau s}} = \frac{Ts + 1}{K(\alpha s + 1)} \frac{1}{1 - \frac{1}{\alpha s + 1} e^{-\tau s}} = \frac{Ts + 1}{K} \frac{1}{\alpha s + 1 - e^{-\tau s}} \approx \frac{Ts + 1}{K(\alpha + \tau)s} \quad (13)$$

which means it is inherently a PI controller $K_p + K_i/s$ with

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

(2) SOPDT. In this case, according to Table 1, the feedback controller is

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

This can be reformulated as a PID controller $K_p + K_i/s + K_d s/(\tau_d s + 1)$ with

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

(3) IPDT. In this case, according to Table 1, the feedback controller is

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

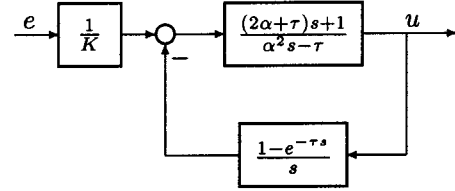


Figure 2. Equivalent feedback controller for IPDT.

which means, again, that the feedback controller is inherently a PI controller $K_p + K_i/s$ with

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

Hence, the proposed controller retains the advantages of the Smith predictor and the advantages of the PID controller. A prominent advantage of the tuning formulas (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 formulas 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 formulas for a PID controller can be obtained using the Padé approximation.

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

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

This is a negative feedback loop of $[(2\alpha + \tau)s + 1]/(\alpha^2 s - \tau)$ through a finite impulse response (FIR) block $(1 - e^{-\tau s})/s$ cascaded by a gain $1/K$, 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

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

Hence, the corresponding sensitivity function is

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

and the complementary sensitivity function is

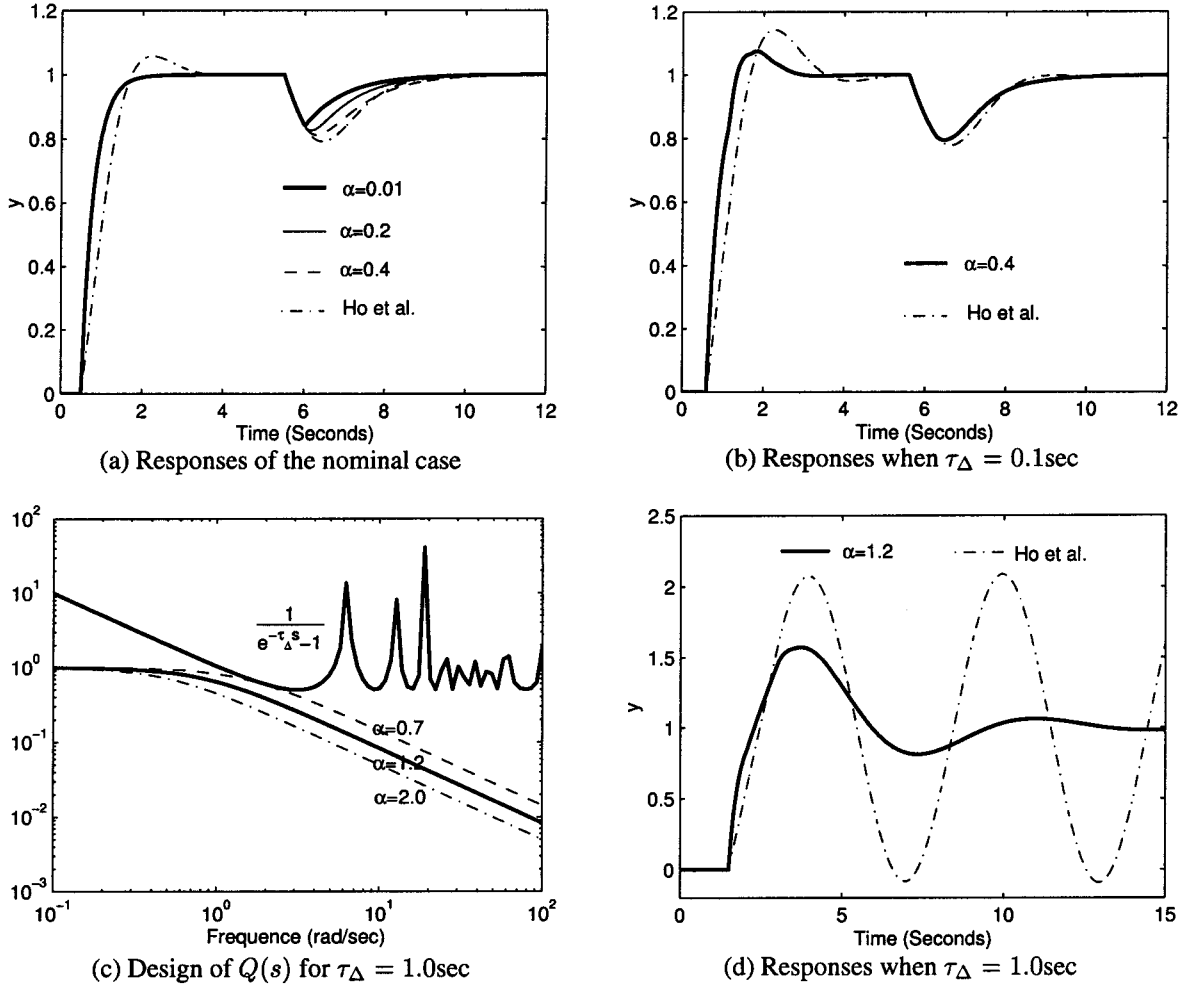
$$T(s) = 1 - S(s) = Q(s) e^{-\tau s} \quad (22)$$

This means that $Q(s)$ not only affects the disturbance response (7) but also affects the robust stability and the

Table 1. Controllers for Typical Processes with Dead Time ($\alpha > 0$)

	$P(s)$	$Q(s)$	$C(s)$	$F(s)$	desired response
FOPDT	$K/(Ts + 1)$	$1/(\alpha s + 1)$	$(Ts + 1)/[K(\alpha s + 1)]$	$(\alpha s + 1)/(\lambda s + 1)$	$e^{-\tau s}/(\lambda s + 1)$
SOPDT	$K/(T^2 s^2 + 2\mu Ts + 1)$	$1/(\alpha s + 1)^2$	$(T^2 s^2 + 2\mu Ts + 1)/[K(\alpha s + 1)^2]$	$(\alpha s + 1)^2/(\lambda^2 s^2 + 2\lambda\zeta s + 1)$	$e^{-\tau s}/(\lambda^2 s^2 + 2\lambda\zeta s + 1)$
IPDT ^a	K/s	$[(2\alpha + \tau)s + 1]/(\alpha s + 1)^2$	$[(2\alpha + \tau)s^2 + s]/[K(\alpha s + 1)^2]$	$(\alpha s + 1)^2/\{[\lambda s + 1][(2\alpha + \tau)s + 1]\}$ $(\alpha s + 1)^2/(\lambda^2 s^2 + 2\lambda\zeta s + 1)[(2\alpha + \tau)s + 1]$	$e^{-\tau s}/(\lambda s + 1)$ $e^{-\tau s}/(\lambda^2 s^2 + 2\lambda\zeta s + 1)$

^a 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 $C(s)/[(1 - Q(s)e^{-\tau s})]$ as the structure shown in Figure 2 where the FIR block $(1 - e^{-\tau s})/s$ should be implemented nondynamically.¹

**Figure 3.** Example 1.

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 $\|Q(s)\|_{\infty} < 1/\|\Delta(s)\|_{\infty}$.

Proof. Because

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

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

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

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. Assuming 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 $\|Q(s)\|_{\infty} < 1/\|(1 + \Delta(s))e^{-\tau_{\Delta}s} - 1\|_{\infty}$.

5. Examples

5.1. Example 1: FOPDT. Consider a widely studied process^{7,16}

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

A PI controller was tuned as $C(s) = 1.05(1 + 1/s)$ in ref 7 to obtain a phase margin of 60° and a gain margin of 3. The resulting settling time was about 2.3 s. Here we choose $\lambda = 0.3$ s to obtain a desired settling time of about 1.4 s. If there is no uncertainty, $Q(s) = 1/(\alpha s + 1)$ can be chosen as having a bandwidth broad enough to obtain the desired disturbance response. The responses with $\alpha = 0.01, 0.1$, and 0.4 are shown in Figure 3a and are compared to those of Ho et al. (noted as Ho et al. in the figures). A step disturbance $d = -0.4$ acts at $t = 5$ s. When $\alpha = 0$, 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 of $\tau_{\Delta} = 0.1$ s, the response under $\alpha = 0.4$ is shown in Figure 3b. As can be seen, the proposed controller achieves a much better performance.

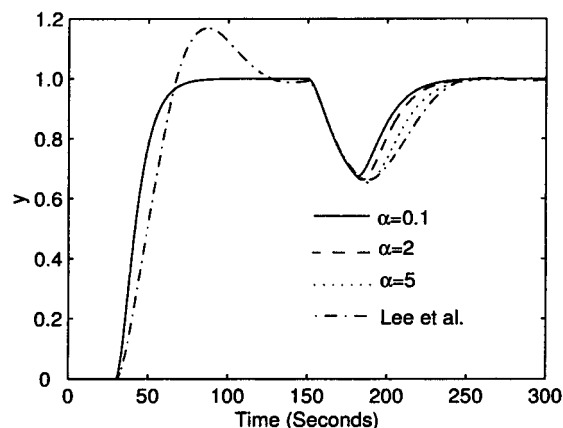
The proposed control scheme has the potential to compromise between the disturbance response and the robust stability, in addition to decoupling the setpoint response and the disturbance response. For a dead-time uncertainty of $\tau_{\Delta} = 1.0$ s, the PI controller $C(s) = 1.05(1 + 1/s)$ critically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

5.2. Example 2: SOPDT. Consider the SOPDT

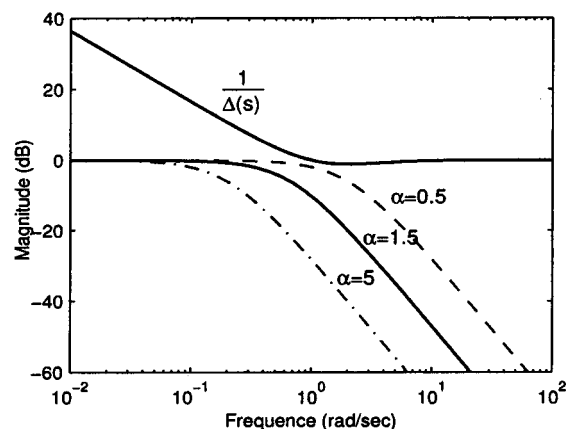
$$G(s) = \frac{e^{-30s}}{(10s+1)^2} \quad (26)$$

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

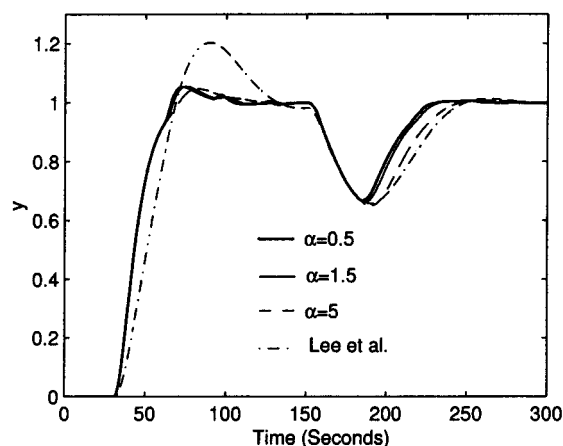
Assume that there exists a multiplicative uncertainty $\Delta(s)$ in the delay-free part, of which the worst case is $\Delta(s) = 1/[(s+1)(0.5s+1)] - 1 = s(0.5s+1.5)/(0.5s^2+1.5s+1)$. To design $Q(s) = 1/(\alpha s + 1)$, the magnitude



(a) Nominal responses



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



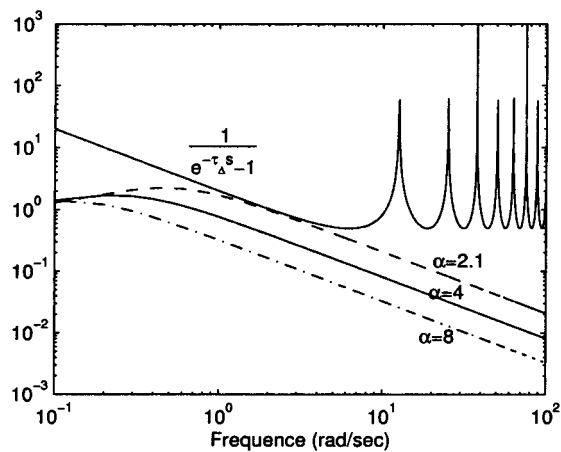
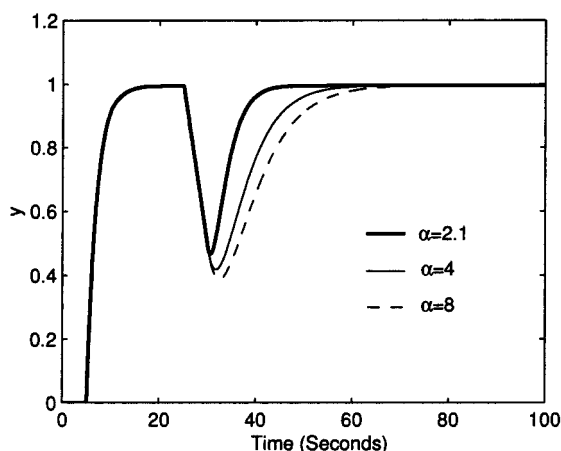
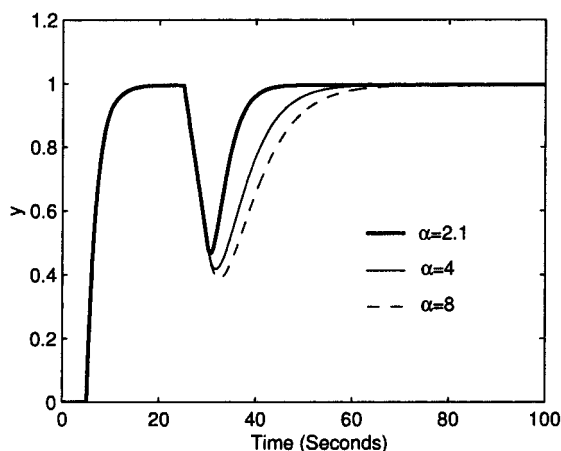
(c) Responses under $\Delta(s) = \frac{s(0.5s+1.5)}{0.5s^2+1.5s+1}$

Figure 4. Example 2.

frequency response of $1/\Delta(s)$ is shown in Figure 4b. The frequency responses of three candidates of $Q(s)$ with $\alpha = 0.5, 1.5$, and 5 are also shown in Figure 4b. The corresponding responses are obtained as shown in Figure 4c. 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}

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

(a) Design of $Q(s)$ (b) Responses when $\tau_\Delta = 0$ (b) Responses when $\tau_\Delta = 0$ **Figure 5.** Example 3.

and assume that there exists a dead-time uncertainty of $0 \leq \tau_\Delta \leq 0.5$ s.

Here, $Q(s) = [(2\alpha + 5)s + 1]/(\alpha s + 1)^2$ is selected with $\alpha = 2.1, 4$, and 8 as shown in Figure 5a. The desired setpoint response is designed with $\lambda = 2$. The responses in the nominal condition are shown in Figure 5b; the responses when $\tau_\Delta = 0.5$ s are shown in Figure 5c. In all cases, a step disturbance $d(t) = 0.1$ acts at $t = 15$ s. 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 2-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 two or three parameters (in addition to model parameters) need to be tuned; either one or two 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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