Improved PI Controller with Delayed or Filtered Integral Mode

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Integral action is almost always included in process control systems to eliminate steady-state offset without uncertain process gain. The open-loop pole, however, at the origin of the integral term causes some problems such as integral windup. Various methods to solve these problems were studied. For better control performance and robustness, a filter was added to the integral term, which decouples the effective frequency ranges between the integral and proportional terms without degradation of the integral action. It produces a phase lead in a certain frequency range without having a derivative term, enhancing the control performances and stability robustness. Based on the internal model control method or the direct synthesis method, tuning rules for the proposed controller are given.

Introduction

An integral term is almost always used for the feedback controller to eliminate steady-state offset. However, it has an open-loop pole at the origin, which causes difficulties in obtaining fast closed-loop responses. The integral term is dominant at low frequencies compared with the proportional and derivative terms; hence, the term may be applied at a slower rate. With this concept, Lee and Edgar (2002) proposed a dual-rate control system with improved stability robustness where the integral action is sampled more slowly. The sample and hold in Lee and Edgar (2002) may be approximated with a time delay or a low pass filter (Kuo, 1992). A filtered integral term will also have better stability robustness. We show that a time delay or a low pass filter added to the integral term can increase the gain and phase margins for some processes.

Use of a time delay element in feedback controller is not new. Some controllers such as the Smith predictor (Smith, 1959), PIDτ_d controller (Shinskey, 1994), and the internal model controller (Morari and Zafiriou, 1989) use time delays intentionally in their structures. Shinskey's PIDτ_d controller is functionally equivalent to the Smith predictor, but it can be tuned more easily (Shinskey, 1996). Suh and Bien (1979) presented the proportional minus delay controller, which performs an averaged derivative action, and, thus, can replace the conventional proportional derivative controller. Kwon et al. (1990) presented a proportional-hereditary controller for a multivariable process with guaranteed stability and improved performance. Zhong et al. (2000) presented a time delay filter for an input shaping of the reference signal. These references show that time delay can be used in the controller design for improved performances. A time delay or a low pass filter is applied here to the integral term for better performances and robustness of the closed-loop system.

The derivative term in the proportional-integral-derivative (PID) controller produces phase lead, lowering the overshoot of the proportional-integral (PI) control system and enhancing robustness. However, the derivative term amplifies the high frequency noise and may cause vigorous control actions. Alternatively, a time delay or a low pass filter added to the integral term also shows phase lead for a certain frequency range and can replace the derivative term without differentiating signals. It expands bandwidths of control systems without increasing the peak amplitude ratios much. Because there is no explicit differentiation of process output signals, the proposed controllers can be used for processes under noisy environments. Several simulations show that the proposed

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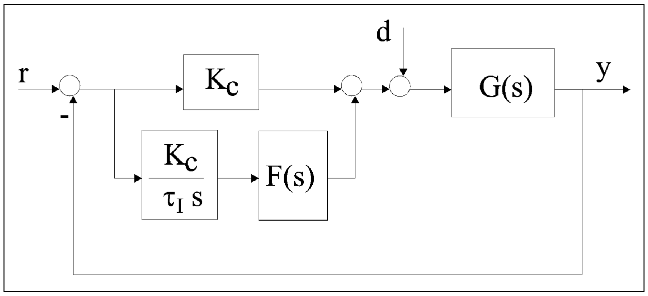

Figure 1. Control system with a filtered integral term.

controllers can approximate PID controllers well when very fast controls are not required.

Bode plots of the proposed controllers with delayed or filtered integral mode are very similar to those of the internal model controller (IMC) (Morari and Zafiriou, 1989). Internal model controllers and their approximate PID controllers provide excellent control performances for various processes. Following Lee et al. (1998), analytic tuning rules for the proposed controllers with filtered integral mode are derived by approximating the internal model controllers. Tuning rules for some processes such as integrating processes where the IMC method does not work well are also obtained by applying the IMC method to the system pre-compensated with a proportional controller (Kwak et al., 1997), resulting in a two degree of freedom controller.

Delayed or Filtered Integral Mode

A control system with a dynamic filter $F(s)$ in the integral term is investigated (Figure 1)

$$C(s) = K_c\left[1 + \frac{1}{\tau_I s}F(s)\right] \tag{1}$$

Two types of filters which reduce undesirable effects of the integral term on stability are considered here. The first filter is a time delay

$$F(s) = \exp(-\theta_F s) \tag{2}$$

which is called a proportional and delayed-integral (PDI) controller. The other is a first-order low pass filter

$$F(s) = 1/(\tau_F s + 1) \tag{3}$$

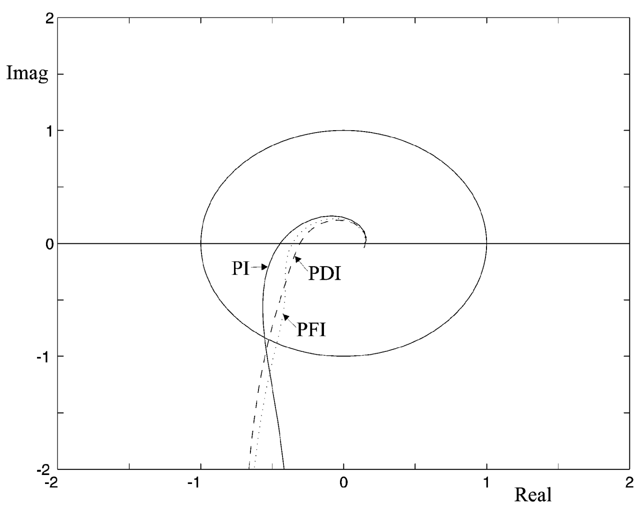

Figure 2. Nyquist plots of PI, PDI and PFI control systems for the process of $G(s) = \exp(-0.5s)/(s+1)$.

The controller gain and integral time are designed by the IMC-PI method with $\lambda = 0.85$. The filter time constant for PFI controller and the time delay for PDI controller are both set to 0.4.

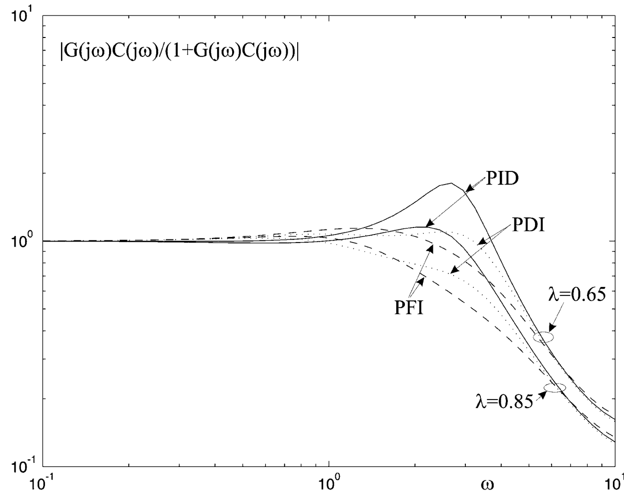

Figure 3. Amplitude ratio plots of closed-loop system for the process of $G(s) = \exp(-0.5s)/(s+1)$.

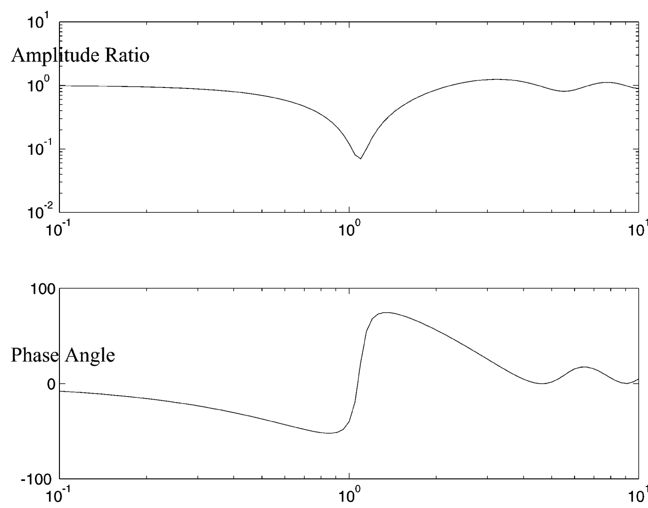

Figure 4. Bode plot for the controller factor $1 + [\exp(-\theta_F s) - 1]/(\tau_I s + 1)$ where $\theta_F = 1.4$ and $\tau_I = 1$.

Table 1. IMC-Based Tuning Rules

Method	Process: $G(s)$	Controller: $C(s)=\frac{1}{s}(\alpha_0+\alpha_1 s+\alpha_2 s^2+\cdots)$
IMC	FOPTD: $\frac{k\exp(-\theta s)}{\tau s+1}$	$\alpha_0=\frac{1}{k(\lambda+\theta)}$, $\alpha_1=\alpha_0\left[\tau+\frac{\theta^2}{2(\lambda+\theta)}\right]$, $\alpha_2=\alpha_0\left[\frac{3\tau\theta^2-\theta^3}{6(\lambda+\theta)}+\frac{\theta^4}{4(\lambda+\theta)^2}\right]$
	SOPTD: $\frac{k\exp(-\theta s)}{\tau^2 s^2+2\zeta\tau s+1}$	$\alpha_0=\frac{1}{k(2\lambda+\theta)}$, $\alpha_1=\alpha_0\left[2\zeta\tau+\frac{\theta^2/2-\lambda^2}{2\lambda+\theta}\right]$, $\alpha_2=\alpha_0\left[\tau^2-\frac{\theta^3}{6(2\lambda+\theta)}\right]+\alpha_1\frac{\theta^2/2-\lambda^2}{2\lambda+\theta}$
PI*		$K_c=\alpha_1$, $\tau_1=\alpha_1/\alpha_0$
PID*		$K_c=\alpha_1$, $\tau_1=\alpha_1/\alpha_0$, $\tau_D=\alpha_2/\alpha_1$
PDI		$K_c=\alpha_1+\sqrt{2\alpha_0\alpha_2}$, $\tau_I=\alpha_1/\alpha_0+\sqrt{2\alpha_2/\alpha_0}$, $\theta_F=\sqrt{2\alpha_2/\alpha_0}$
PFI		$K_c=\alpha_1+\sqrt{\alpha_0\alpha_2}$, $\tau_I=\alpha_1/\alpha_0+\sqrt{\alpha_2/\alpha_0}$, $\tau_F=\sqrt{\alpha_2/\alpha_0}$

*See Lee et al. (1998).

which is called a proportional and filtered-integral (PFI) controller.

We illustrate the effect of $F(s)$ with an example. Consider a first-order plus time delay process, $G(s)=\exp(-0.5s)/(s+1)$. A PI controller can be designed by the IMC-PI method (Morari and Zafiriou, 1989) as $C(s)=K_c[1+1/(\tau_I s)]$ with $K_c=2.5/\lambda$ and $\tau_I=1.25$, where λ is the design parameter for the IMC method. For $\lambda=0.85$ recommended by Morari and Zafiriou (1989), Nyquist plots for the PI, PDI, and PFI controllers with $\theta_F=0.4$ and $\tau_F=0.4$, respectively, are shown in Figure 2. Nyquist plot $G(j\omega)C(j\omega)$ vs. ω in the complex plane provides useful information about the robustness of control systems. For a stable process, the closed-loop system becomes unstable if the Nyquist plot encircles the point of $-1+0j$ (Seborg et al., 1989). Gain and phase margins of a stable closed-loop system are represented by distances between the Nyquist plot and the point of $-1+0j$ on the negative real line and the circle of radius 1 in Figure 2, respectively. We can see that both PDI and PFI controllers enlarge the gain and phase margins.

The amplitude ratio plot of the closed-loop transfer function $G(s)C(s)/[1+G(s)C(s)]$ can be used to infer the control performance and robustness. That is, the bandwidth and peak amplitude ratio of the closed-loop transfer function are closely related to the speed and robustness of the closed-loop system, respectively (Morari and Zafiriou, 1989). Figure 3 shows the amplitude ratio plots for the control systems of the above process with two different IMC parameters. The PDI and PFI controllers decrease the peak amplitude ratios, as expected by the Nyquist plots of Figure 2. They also decrease the bandwidths, resulting in slower control responses. However, bandwidths of the PDI and PFI control systems can be increased by decreasing the IMC parameter λ without making the peak amplitude ratio as large. Hence, PDI and PFI control systems with fast responses and robustness compared with conventional PI control systems can be obtained.

The controller in Figure 1 can implement general proper controllers when no limit is imposed on the structure of $F(s)$. For example, PID controllers with a first-order filter can be rearranged to the form of Figure 1 as

$$C(s)=K_c\left(1+\frac{1}{\tau_I s}+\tau_D s\right)\frac{1}{\tau_F s+1}$$
$$=k_1+\frac{k_2}{s}\,\frac{k_3 s+1}{k_4 s+1}$$

where $k_1=K_c\tau_D/\tau_F$, $k_2=K_c/\tau_I$, $k_3=\tau_1(1-\tau_D/\tau_F)$ and $k_4=\tau_F$. The controller structure in Figure 1 may be used to implement general control systems.

The PI controller with a filtered integral term can be rearranged as

$$C(s)=K_c+\frac{K_c}{\tau_I s}\,\frac{1}{\tau_F s+1}=K_c\left(1+\frac{1}{\tau_I s}+\tau_F s\right)\frac{1}{\tau_F s+1}$$

It is a kind of PID controller with a filter. Like the derivative term, a low pass filter added to the integral term can improve the control performances. Since the proposed low pass filter does not amplify high frequency noise, it can be used effectively for processes under noisy environments. The PI controller with a delayed integral term can be

$$C(s)=K_c+\frac{K_c\exp(-\theta_F s)}{\tau_I s}$$
$$=K_c\left[1+\frac{1}{\tau_I s}+\frac{\exp(-\theta_F s)-1}{\tau_I s}\right]$$
$$=K_c\left(1+\frac{1}{\tau_I s}\right)\left[1+\frac{\exp(-\theta_F s)-1}{\tau_I s+1}\right]$$

Typical Bode plot of the factor $1+(\exp(-\theta_F s)-1)/(\tau_I s+1)$ is shown in Figure 4. We can see a considerable phase lead at a certain frequency range. Control systems such as PID and

Smith predictor suffer from large amplitude ratios at the cost of phase leads. On the other hand, our delayed integral term does not increase the amplitude ratio much for the phase lead. This phase lead will reduce the phase lag due to the process time delay, enhancing stability margins.

Design Based on the Internal Model Controller

The proposed control method can be used to improve existing PI control systems by choosing θ_F or τ_F to lower overshoot or to enlarge the gain and phase margins. However, this tuning procedure is not optimal because K_c and τ_I are determined without considering θ_F or τ_iF. For better tuning of the proposed controllers, tuning rules which design simultaneously the PI parameters and the filter parameter (θ_F or τ_F) are required.

We can design PDI or PFI controllers by approximating the internal model controllers. For this, the Pade method employed by Lee et al. (1998) in designing PID controllers is used. For a first-order plus time delay (FOPTD) model

$$G(s) = \frac{k\,\exp(-\theta s)}{\tau s + 1} \tag{4}$$

the internal model controller becomes

$$C_{\mathrm{IMC}}(s) = \frac{\tau s + 1}{k[\lambda s + 1 - \exp(-\theta s)]} = \frac{1}{s}\left[\frac{1}{k(\lambda+\theta)} + \frac{2\tau(\lambda+\theta)+\theta^2}{2k(\lambda+\theta)^2}s + \frac{6\tau\theta^2(\lambda+\theta)+\theta^3(\theta-2\lambda)}{12k(\lambda+\theta)^3}s^2 + \cdots\right] \tag{5}$$

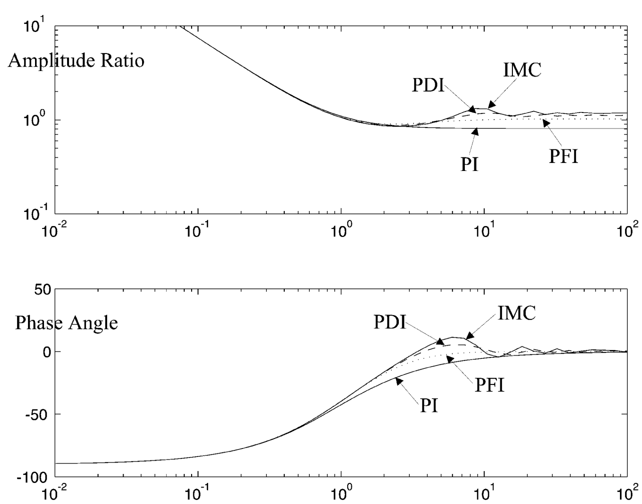

Figure 5. Bode plots of $G_c(s)$ tuned for the process $G(s) = \exp(-0.5s)/(s+1)$.

For the PDI controller, we have

$$C_{\mathrm{PDI}}(s) = k_1 + \frac{k_2}{s}\exp(-\theta_F s) = \frac{1}{s}\left[k_2 + (k_1 - k_2\theta_F)s + k_2\frac{\theta_F^2}{2}s^2 + \cdots\right] \tag{6}$$

and, for the PFI controller

$$C_{\mathrm{PFI}}(s) = k_1 + \frac{k_2}{s}\,\frac{1}{\tau_F s + 1} = \frac{1}{s}\left[k_2 + (k_1 - k_2\tau_F)s + k_2\tau_F^2 s^2 + \cdots\right] \tag{7}$$

By matching series expansion of $C_{\mathrm{PDI}}(s)$ or $C_{\mathrm{PFI}}(s)$ with that of $C_{\mathrm{IMC}}(s)$, parameters for the proposed controllers can be obtained. This technique can also be applied to any analytic process model including the second-order plus time delay (SOPTD) model. Results are shown in Table 1.

Bode plots of the above three controllers for the control system with $k=1$, $\tau=1$, $\theta=0.5$, and $\lambda=0.85$ are shown in Figure 5. We can see that frequency responses of the proposed PDI and PFI controllers are similar to those of the internal model controller.

Design Based on Two Step IMC Method

The above IMC method is very simple and effective for various processes. However, as noted by many authors (Shinskey, 1994; Morari and Zafiriou, 1989), its load responses can be very poor for some processes because it is based on the pole/zero cancellation. For example, the IMC parameter λ can be set to be very small for fast set point responses when the process time delay is small compared with the process time constant. Then, set point responses are fast,

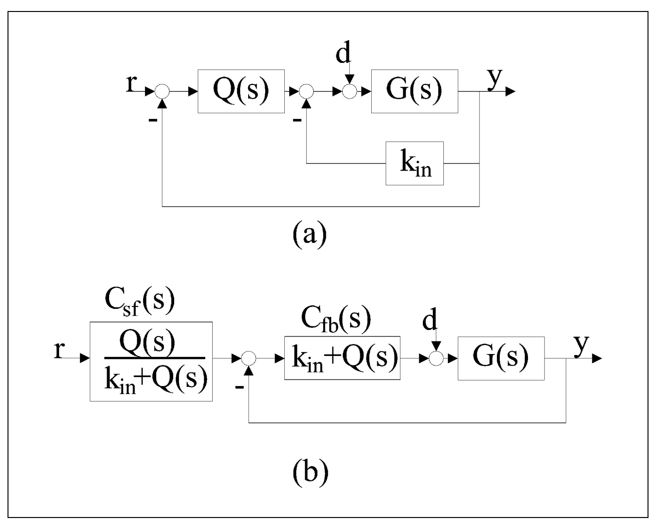

Figure 6. (a) Control system with an inner P controller; (b) equivalent two degree of freedom control system.

Table 2. Two-Step IMC-Based Turning Rules

Method	Process: $G(s)$	Controller: $Q(s)=\frac{1}{s}(\alpha_0+\alpha_1 s+\alpha_2 s^2+\cdots)$
IMC	FOPTD: $\frac{k\exp(-\theta s)}{\tau s+1}$	$k_{in}=k_u/4$, k_u = ultimate gain $\alpha_0=\frac{1+k_{in}k}{k(\lambda+\theta)},\ \alpha_1=\alpha_0\left[\frac{\tau-k_{in}k\theta}{1+k_{in}k}+\frac{\theta^2}{2(\lambda+\theta)}\right],$ $\alpha_2=\alpha_0\left[\frac{k_{in}k\theta^2}{2(1+k_{in}k)}-\frac{\theta^3}{6(\lambda+\theta)}+\frac{\theta^4}{4(\lambda+\theta)^2}+\frac{(\tau-k_{in}k\theta)\theta^2}{2(1+k_{in}k)(\lambda+\theta)}\right]$
	Integrating: $\frac{k\exp(-\theta s)}{s}$	$k_{in}=k_u/4$, k_u = ultimate gain $\alpha_0=\frac{k_{in}}{\lambda+\theta},\ \alpha_1=\alpha_0\left[\frac{1}{k_{in}k}-\theta+\frac{\theta^2}{2(\lambda+\theta)}\right],$ $\alpha_2=\alpha_0\left[\frac{\theta^2}{2}-\frac{\theta^3}{6(\lambda+\theta)}+\frac{\theta^4}{4(\lambda+\theta)^2}+\frac{(1-k_{in}k\theta)\theta^2}{2k_{in}k(\lambda+\theta)}\right]$
	Integrating: $\frac{k\exp(-\theta s)}{s(\tau s+1)}$	$k_{in}=k_u/4$, k_u = ultimate gain $\alpha_0=\frac{k_{in}}{\lambda+\theta},\ \alpha_1=\alpha_0\left[\frac{1}{k_{in}k}-\theta+\frac{\theta^2}{2(\lambda+\theta)}\right],$ $\alpha_2=\alpha_0\left[\frac{\tau}{k_{in}k}+\frac{\theta^2}{2}-\frac{\theta^3}{6(\lambda+\theta)}+\frac{\theta^4}{4(\lambda+\theta)^2}+\frac{(1-k_{in}k\theta)\theta^2}{2k_{in}k(\lambda+\theta)}\right]$
	Unstable: $\frac{k\exp(-\theta s)}{\tau s-1}$	$k_{in}=1/\sqrt{\lvert G(j\omega_u)\rvert\lvert G(0)\rvert}$, ω_u = ultimate frequency* $\alpha_0=\frac{k_{in}k-1}{k(\lambda+\theta)},\ \alpha_1=\alpha_0\left[\frac{\tau-k_{in}k\theta}{k_{in}k-1}+\frac{\theta^2}{2(\lambda+\theta)}\right],$ $\alpha_2=\alpha_0\left[\frac{k_{in}k\theta^2}{2(k_{in}k-1)}-\frac{\theta^3}{6(\lambda+\theta)}+\frac{\theta^4}{4(\lambda+\theta)^2}+\frac{(\tau-k_{in}k\theta)\theta^2}{2(k_{in}k-1)(\lambda+\theta)}\right]$
PI		$K_c=\alpha_1,\ \tau_I=\alpha_1/\alpha_0$
PID		$K_c=\alpha_1,\ \tau_I=\alpha_1/\alpha_0,\ \tau_D=\alpha_2/\alpha_1$
PDI		$K_c=\alpha_1+\sqrt{2\alpha_0\alpha_2},\ \tau_I=\alpha_1/\alpha_0+\sqrt{2\alpha_2/\alpha_0},\ \theta_F=\sqrt{2\alpha_2/\alpha_0}$
PFI		$K_c=\alpha_1+\sqrt{\alpha_0\alpha_2},\ \tau_I=\alpha_1/\alpha_0+\sqrt{\alpha_2/\alpha_0},\ \tau_F=\sqrt{\alpha_2/\alpha_0}$

*See De Paor and O'Malley (1989).

but the load responses for disturbances in the process input can be slow due to the slow process pole. Sung and Lee (1996) showed that two degree of freedom controllers are required for these processes. Various methods to solve the above disadvantage of the IMC method are available. A two step method (Kwak et al., 1997) can be used for this purpose, where a P control system is designed first and then a PID controller is designed for the compensated system, as in Fig-

Table 3. Controller Parameters and Properties of Control Systems

Process	Method	λ	K_c	τ_I	τ_D	θ_F	k_{in}	Over-shoot	Peak Amplitude Ratio	Band-width
$\frac{\exp(-0.5s)}{s+1}$	PI	0.3	1.445	1.156				1.16	1.18	3.4
	PID	0.3	1.445	1.156	0.134			1.00	1.00	3.1
	PDI	0.3	2.140	1.712		0.556		1.05	1.00	4.4
$\frac{\exp(-s)}{9s^2+4s+1}$	PI	1.5	0.891	3.563				1.28	1.77	.51
	PID	1.5	0.891	3.563	2.077			1.02	1.00	.35
	PDI	1.5	1.852	7.410		3.847		1.03	1.00	.66
$\frac{\exp(-s)}{s}$	PI	1	0.353	1.797			0.393	1.15	1.21	1.3
	PID	1	0.353	1.797	0.228		0.393	1.00	1.00	.94
	PDI	1	1.004	5.112		1.316	0.393	1.01	1.00	1.6

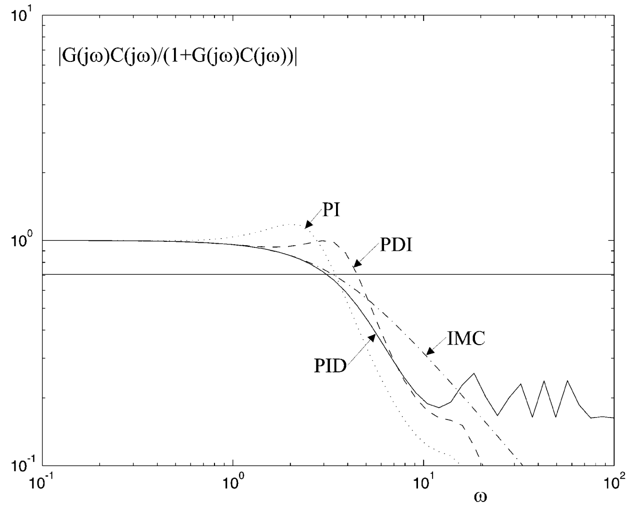

Figure 7. Amplitude ratio plots of IMC, PI, PID and PDI control systems for the process of $G(s) = \exp(-0.5s)/(s+1)$.

All controllers are designed from the IMC controller.

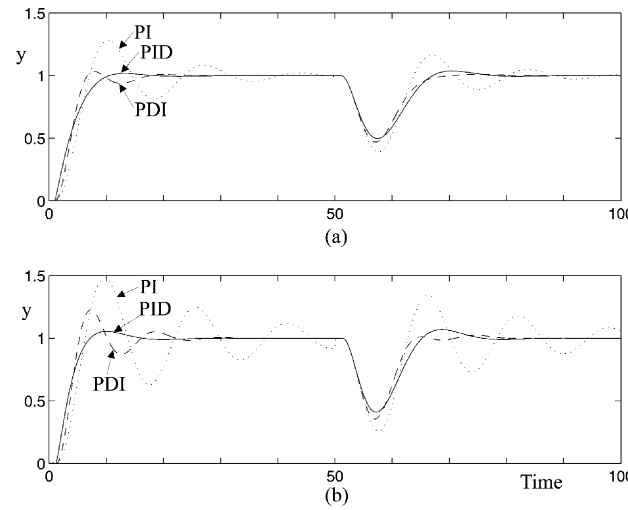

Figure 9. Step set point and step load responses for the process: (a) $G(s) = \exp(-s)/(9s^2+4s+1)$ with no model parameter uncertainties; (b) with increased process gain and time delay by 25%.

ure 6. The control system of Figure 6a can be rearranged to be the two degree of freedom controller form (Figure 6b). This technique can also be applied to unstable processes including integrating processes.

First the inner P control system is designed. Then, the closed-loop system becomes $G(s)/(1+k_{\text{in}}G(s))$ and, applying the previous IMC method to this transfer function, we can obtain the outer controller $Q(s)$. For a first-order plus time delay (FOPTD) process or an integrating process, the Ziegler-Nichols tuning rule with

$$k_{\text{in}} = k_u/4$$

is often used for the inner P controller (Kwak et al., 1997), where k_u is the ultimate gain of the process. For an unstable process of $G(s) = k[\exp(-\theta s)]/(\tau s - 1)$, De Paor and O'Malley (1989) proposed the following P controller gain,

$$k_{\text{in}} = 1/\sqrt{|G(j\omega_u)\,\|\,G(0)|}$$

where ω_u is the ultimate frequency. The feedback controller becomes $C_{fb}(s) = k_{\text{in}} + Q(s)$ and is shown in Table 2.

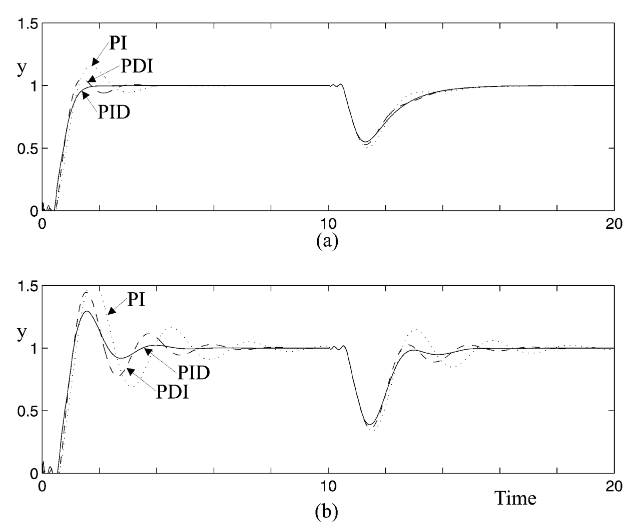

Figure 8. (a) Step set point responses and step load responses for the process of $G(s) = \exp(-0.5s)/(s+1)$ with no model parameter uncertainties; (b) step set point responses and step load responses for the process with increased process gain and time delay by 25%.

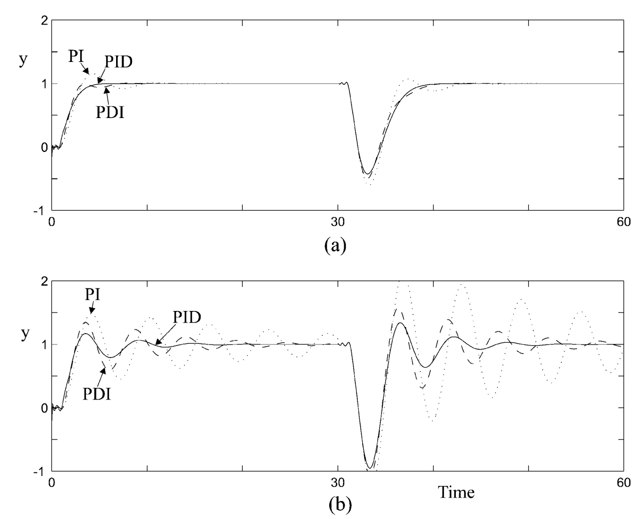

Figure 10. Step set point and step load responses for the process: (a) $G(s) = \exp(-s)/s$ with no model parameter uncertainties; (b) with increased process gain and time delay by 25%.

Examples

Simulations show that control performances of PDI or PFI controllers are very similar. Hence, for brevity, the PDI controllers designed by tuning rules in Tables 1 and 2 are compared with PI and PID controllers. For simulations, time delays are all approximated by the 5/5 Pade approximation.

FOPTD process

The proposed methods are applied to the first-order plus time delay process, $G(s) = \exp(-0.5s)/(s+1)$. Controller parameters and some closed-loop system properties are shown in Table 3. Figure 7 shows the amplitude ratio plots for the closed-loop transfer function $G(s)C(s)/(1+G(s)C(s))$. The PID controller can approximate well the IMC controller for frequencies up to the bandwidth. At high frequencies over $\omega = 10$, the amplitude ratio of PID controller is high due to the derivative term in the controller and, hence, it is sensitive for the high frequency disturbances. The PI control system shows a peak in the amplitude ratio plot and has bandwidth similar to that of the PID controller. Both PI and PID control systems will have similar control speeds. However, the PI control system will be more oscillatory due to the peak in amplitude ratio. The PDI control system lowers the peak amplitude ratio of the PI control system and enlarges the bandwidth, resulting in the fastest control speed.

Figure 8a shows step set point responses and step load responses for process without parameter uncertainties. The PID controller behaves similar to the internal model controller, showing the first-order like response of the internal model controller. As expected from Table 3 and Figure 7, the PDI controller shows somewhat oscillatory responses and has the fastest rise time.

Figure 8b shows responses for the process whose gain and time delay are increased by 25%. The PDI controller shows better robustness than the PI controller. This can be inferred from peak amplitude ratio of the closed-loop transfer function in Table 3 and Figure 7. By increasing λ a little, the PDI control system can be made less oscillatory while having control speed comparable with the PID control system. When very small λ (that is, very fast control) is not required, the PDI controller can replace the PID controller.

SOPTD process

For the slightly underdamped process of $G(s) = \exp(-s)/(9s^2+4s+1)$, the proposed PDI controller is compared with the PI and PID controllers, which approximate the IMC controller. Controller parameters and some closed-loop system properties are shown in Table 3. Figure 9a shows the step set point responses and the step load responses for the process without parameter uncertainties, which shows that the proposed PDI controller behaves similar to the PID controller. Figure 9b shows responses for the process whose gain and time delay are increased by 25%. The same conclusion can be drawn as for the FOPTD processes.

Integrating process

Two step IMC-based method is applied to the integrating process of $G(s) = \exp(-s)/s$. Controller parameters and some closed-loop system properties are shown in Table 3. Two degree of freedom control systems in Figure 6b are simulated. Figure 10a shows the step set point responses and the step load responses for the process without parameter uncertainties. Figure 10b shows responses for the process whose gain and time delay are increased by 25%. The PDI controller has better robustness than the PI controller.

Conclusions

Controllers with delayed or filtered integral terms are proposed. A time delay or a low pass filter added to the integral term is shown to enlarge the gain and phase margins and reduce overshoot in the step set point response of a PI control system. Gain and phase margins of a PI control system can be enhanced usually by introducing the derivative term. However, the derivative term amplifies high frequency signals and cannot be applied for processes under noisy environments. Alternatively, because the proposed controllers have no derivative terms, they can be effectively used for processes under noisy environments, replacing the PID controllers.

Bode plots of proposed controllers are very similar to those of the internal model controllers. Based on this, analytic tuning rules for the proposed controllers which approximate the internal model controllers are derived.

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Literature Cited

De Paor, A. M., and M. J. O'Malley, "Controllers of Ziegler-Nichols Type for Unstable Process with Time Delay," *Int. J. Control*, **49**, 1273 (1989).

Kuo, B. C., *Digital Control Systems*, 2nd ed., Sanders College Pub., New York (1992).

Kwak, H. J., S. W. Sung, and I. B. Lee, "On-line Process Identification and Autotuning for Integrating Processes," *Ind. Eng. Chem. Res.*, **36**, 5329 (1997).

Kwon, W. H., G. W. Lee, and S. W. Kim, "Performance Improvement Using Time Delays in Multivariable Controller Design," *Int. J. Control*, **52**, 1455 (1990).

Lee, J., and T. F. Edgar, "Dual-rate Control Systems for Single-Input Single-Output Processes," *J. of Process Control*, in press (2002).

Lee, Y., M. Lee, S. Park, and C. Brosilow, "PID Controller Tuning to Obtain the Desired Closed-loop Response: Single Input and Single Output System, *AIChE J.*, **44**, 106 (1998).

Morari, M., and E. Zafiriou, *Robust Process Control*, Prentice-Hall, New York (1989).

Seborg, D. E., T. F. Edgar, and D. A. Mellichamp, *Process Dynamics and Control*, Wiley, New York (1989).

Shinskey, F. G., *Feedback Controllers for the Process Industries*, McGraw-Hill, New York (1994).

Shinskey, F. G., *Process Control Systems, Application, Design and Tuning*, 4th ed., McGraw-Hill, New York (1996).

Smith, O. J. M., "A Controller to Overcome Dead Time," *ISA J.*, **6**, 28 (1959).

Suh, I. H., and Z. Bien, "Proportional Minus Delay Controller," *IEEE Trans. Automatic Control*, AC-24, 370 (1979).

Sung, S. W., and I. B. Lee, "Limitations and Countermeasures of PID Controllers, " *Ind. Eng. Chem. Res.*, **35**, 2596 (1996).

Zhong, Q. C., J. Y. Xie, and Q. Jia, "Time Delay Filter-Based Deadbeat Control of Process with Dead Time", *Ind. Eng. Chem. Res.*, **39**, 2024 (2000).

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