Analytical Design of Robust PID Filter Controller for Processes with Time Delay

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1. Introduction

Although a number of advanced control techniques have been reported in the enormous literature, the IMC structure, the control structure containing the internal model of controlled plant that was spread mainly by Garcia and Morari (1982), is still one of the most widely used control schemes in the process industries due to its simplicity, flexibility, and apprehensibility. Therefore, over the last two decades numerous academic and control engineers have utilized the IMC principle to design the PID-type controller, which is usually called as the IMC-PID controller. The most important advantage of the IMC-PID tuning rules is that the tradeoffs between the closed-loop performance and robustness can be directly obtained by using only a single tuning parameter (Garcia and Morari, 1982; Rivera et al., 1986) which is related to the closed-loop time constant. Moreover, the IMC-PID tuning rules have been proved to be good set-point tracking but sluggish disturbance rejection, which becomes severely for the process with a small time-delay/time constant ratio. However, it should be noted that the disturbance rejection is more important than the set-point tracking for many process control applications, and thus it has recently become an imperative issue for many researchers.

The present study is focused on the design of the PID controller cascaded with the lead-lag filter to fulfill various control purposes: tuning rules should be simple, analytical form, model-based, and easy to implement in the practice with the excellent performance for both the regulatory and servo problems.

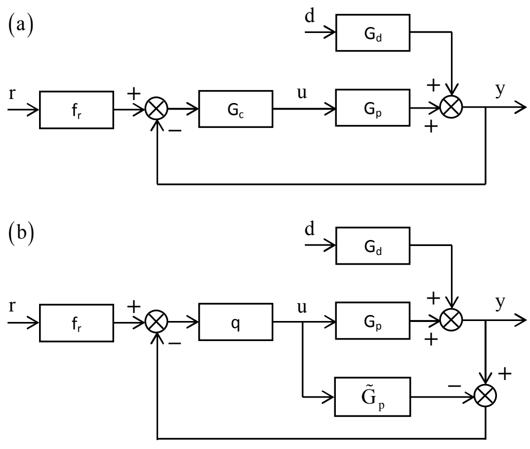

Fig. 1 Block diagram of feedback control strategies. (a) Classical feedback control. (b) Internal model control.

2. IMC Approach for the PID Filter Controller Design

According to the standard block diagram of the feedback control strategies as shown in Fig.1, where $G_P(s)$, $\tilde{G}_P(s)$, $G_c(s)$, $q(s)$, and $f_r(s)$ denote the process, the process model, the equivalent feedback controller, the IMC controller, and the set-point filter, respectively. Assume that $y(s)$, $r(s)$, $d(s)$, and $u(s)$ correspond to the controlled output, set-point input, disturbance input, and manipulated variables. If there is no model error (i.e., $G_P(s) = \tilde{G}_P(s)$), then the set-point and disturbance responses in the IMC control structure can be simplified as:

$$y(s)=G_P(s)q(s)f_r(s)r(s)+\left[1-\tilde{G}_P(s)q(s)\right]G_d(s)d(s) \tag{1}$$

In accordance with the IMC parameterization (Morari and Zafirio, 1989), the process model $\tilde{G}_P(s)$ is factored into two parts:

$$\tilde{G}_P(s)=p_m(s)p_A(s) \tag{2}$$

where $p_m(s)$ is the portion of the model inverted by the controller (minimum phase), $p_A(s)$ is the portion of the model not inverted by the controller (it is the non-minimum phase that may be included the dead time and/or right half plane zeros and chosen to be all-pass), and the requirement that $p_A(0)=1$ is necessary for the controlled variable to track its set-point.

The IMC controller $q(s)$ can be designed as $q(s)=p_m^{-1}(s)f(s)$.

For the 2DOF control structure, the IMC filter $f(s)$ is chosen for enhanced performance as follows:

$$f(s)=\frac{\sum_{i=1}^{m}\beta_i s^i+1}{(\lambda s+1)^n} \tag{3}$$

where λ is an adjustable parameter, which can be utilized for the tradeoffs between the performance and robustness. The integer n is selected to be large enough for the IMC controller proper. The parameter β_i is determined to cancel the poles near zero in $G_d(s)$.

$$1-G_P(s)q(s)\Big|_{s=z_{d1},z_{d2},\dots,z_{dm}}=\left|1-\frac{p_A(s)\left(\sum_{i=1}^{m}\beta_i s^i+1\right)}{(\lambda s+1)^n}\right|_{s=z_{d1},z_{d2},\dots,z_{dm}}=0 \tag{4}$$

The IMC controller can be designed as follows:

$$q(s)=p_m^{-1}(s)\frac{\left(\sum_{i=1}^{m}\beta_i s^i+1\right)}{(\lambda s+1)^n} \tag{5}$$

Therefore, the ideal feedback controller for achieving the desired loop response can be easily obtained by

$$G_c(s)=\frac{q(s)}{1-\tilde{G}_P(s)q(s)}=\frac{p_m^{-1}(s)\left(\sum_{i=1}^{m}\beta_i s^i+1\right)}{(\lambda s+1)^n-p_A(s)\left(\sum_{i=1}^{m}\beta_i s^i+1\right)} \tag{6}$$

The resulting controller given by Eq. 6 does not have the standard PID-type controller form despite that it is physically realizable. Consequently, it is necessary to convert it into the suitable PID-type controller form more closely by using the clever approximation techniques. In this paper, a 3/2 Padé approximation is utilized in the different manner with previous design methods in terms of the most closely PID controller approximates the ideal feedback controller.

3. IMC-PID Tuning Rules

The FOPDT process model is one of the most widely used models in the process industries, which is usually considered to design the PID controller. The process transfer function is given as:

$$G_P(s)=\frac{Ke^{-\theta s}}{(\tau s+1)} \tag{7}$$

The standard PID controller in series with second-order lead-lag filter is given as

$$G_c(s)=K_c\left(1+\frac{1}{\tau_I s}+\tau_D s\right)\frac{1+cs+ds^2}{1+as+bs^2}=\frac{1}{s}\left(\frac{K_c}{\tau_I}\right)\left(1+\tau_I s+\tau_I\tau_D s^2\right)\left(\frac{1+cs+ds^2}{1+as+bs^2}\right) \tag{8}$$

By converting Eq. 6 into Eq. 8, IMC-PID tuning rules can be obtained as follows:

$$\mathrm{K_c} = \frac{2\theta}{5\mathrm{K}(\lambda+\theta)},\ \tau_\mathrm{I} = \frac{2\theta}{5},\ \tau_\mathrm{D} = \frac{\theta}{8},\ a = \frac{\theta(4\lambda-\theta)}{10(\lambda+\theta)},\ b = \frac{\theta^2(3\lambda+\theta)}{60(\lambda+\theta)},\ c=\tau, d=0 \tag{9}$$

For other process models, the aforementioned procedure can also be applied to derive the analytical tuning rules.

4. Simulation Study

Consider the FOPDT process model studied by Lee et al. (1998) as follows:

$$\mathrm{G_p}(s) = \mathrm{G_d}(s) = \frac{e^{-3s}}{10s+1} \tag{10}$$

The performance of the proposed method was compared with those by Lee et al. (1998), Shamsuzzoha and Lee (2009), and Rivera et al. (1986). The controller characteristics are listed in Table 1. The resulting output responses to unit step changes in the set-point (t=0) and disturbance (t=80) are shown in Fig. 2. It is apparent from the table and figure that the proposed PID controller provides the best performance among all four PID controllers for both the disturbance rejection and set-point tracking.

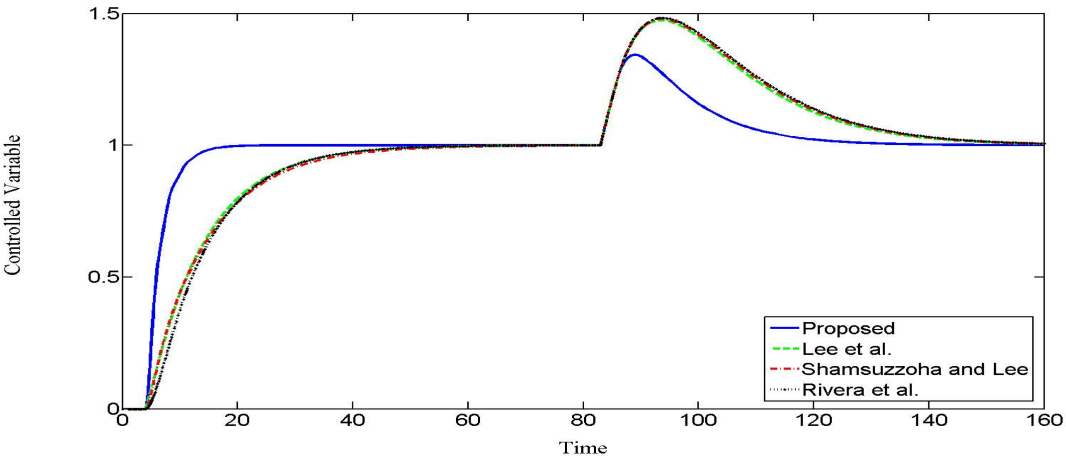

Fig. 2 Simulation results of PID controllers

The robustness of controllers is evaluated by inserting a perturbation uncertainty of ±60% in all three process parameters into the actual process, simultaneously. The simulation results of the model mismatch for various tuning methods are tabulated in Table 2. Obviously, the proposed method shows an enhanced robust performance for both the disturbance rejection and set-point tracking.

Table 1 PID controller parameters and performance matrix

						Set-point		Disturbance	
Tuning methods	$\mathrm{K_C}$	τ_I	τ_D	λ	Ms	IAE	Overshoot	IAE	Overshoot
Proposed[a]	0.208	1.200	0.375	2.780	1.02	5.780	0	5.780	0.347
Lee et al.	0.790	10.34	0.310	10.10	1.20	13.11	0	13.11	0.478
Shamsuzzoha and Lee [b]	0.111	1.500	0.500	10.50	1.20	13.51	0	13.51	0.483
Rivera et al.[c]	0.833	11.50	1.304	10.81	1.20	13.81	0	13.81	0.487

[a] $a=0.2943$, $b=0.4214$, $c=10$, $d=0$

[b] $a=0.5833$, $b=1.1667$, $c=10$, $d=0$

[c] $a=1.1742$, $b=0$, $c=0$, $d=0$

Table 2 Robustness analysis

Tuning methods	+60%				-60%			
	Set-point		Disturbance		Set-point		Disturbance	
	IAE	Overshoot	IAE	Overshoot	IAE	Overshoot	IAE	Overshoot
Proposed	11.11	0.446	5.908	0.504	14.45	0	5.78	0.203
Lee et al.	14.18	0.145	14.43	0.645	32.58	0	13.02	0.271
Shamsuzzoha and Lee	14.10	0.133	14.89	0.652	33.56	0	13.41	0.273
Rivera et al.	15.63	0.161	15.21	0.657	34.29	0	13.70	0.274

5. Conclusions

The design method for the PID controller cascaded with the second-order lead-lag filter was proposed for a variety of the process with time delay. On the basis of the renowned IMC theory, the proposed controller can provide an excellent improvement of performance for the disturbance rejection as well as set-point tracking. The robustness study was also conducted by inserting a perturbation uncertainty in each of the process parameters simultaneously toward the worst-case mismatch models. The results showed that the proposed control systems held robust stability well in both the nominal and the plant-model mismatch cases.

Acknowledgments

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