Korean J. Chem. Eng., **30**(3), 546-558 (2013)
DOI: 10.1007/s11814-012-0161-6

A unified approach to the design of advanced proportional-integral-derivative controllers for time-delay processes

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(*Received 7 July 2012 • accepted 19 September 2012*)

Abstract−A unified approach for the design of proportional-integral-derivative (PID) controllers cascaded with first-order lead-lag filters is proposed for various time-delay processes. The proposed controller's tuning rules are directly derived using the Padé approximation on the basis of internal model control (IMC) for enhanced stability against disturbances. A two-degrees-of-freedom (2DOF) control scheme is employed to cope with both regulatory and servo problems. Simulation is conducted for a broad range of stable, integrating, and unstable processes with time delays. Each simulated controller is tuned to have the same degree of robustness in terms of maximum sensitivity (Ms). The results demonstrate that the proposed controller provides superior disturbance rejection and set-point tracking when compared with recently published PID-type controllers. Controllers' robustness is investigated through the simultaneous introduction of perturbation uncertainties to all process parameters to obtain worst-case process-model mismatch. The process-model mismatch simulation results demonstrate that the proposed method consistently affords superior robustness.

Key words: PID Controller Design, Lead-lag Filter, Disturbance Rejection, Set-point Tracking, Two-degree-of-freedom (2DOF) Control Scheme

INTRODUCTION

The IMC structure [1], a control structure incorporating the internal model of plant control, has been widely utilized in the design of PID-type controllers, usually denoted IMC-PID controllers, because of its simplicity, flexibility, and apprehensibility. The most important advantage of IMC-PID tuning rules is that the tradeoff between closed-loop performance and robustness can be directly obtained using a single parameter related to the closed-loop time constant [1-3]. IMC-PID tuning rules can provide good set-point tracking, but have been lacking regarding disturbance rejection, which can become severe for processes with a small time-delay/time constant ratio. Disturbance rejection is more important than set-point tracking in many process control applications, and thus is an important research topic.

A 2DOF control scheme can be used to improve disturbance performance for various time-delay processes [4-8]. Lee et al. [4] describe a typical application of this novel control scheme, wherein an IMC filter, including a lead term to neglect the process dominant poles suggested by Horn et al. [5], is also used. The controller's performance can be significantly enhanced by a PID controller cascaded with a conventional filter, something easily implementable in modern control hardware. Consequently, several controller tuning rules have been reported despite PID controllers cascading with conventional filters being often more complicated than a conventional PID controller for processes with time delay. However, this difficulty can be overcome by using appropriate low-order Padé approximations of the time delay term in the process model. Therefore, the PID-type controller can be indirectly obtained by considering the Padé approximations. Accordingly, first-order Padé approximations have been used by a number of authors [2,3,5,9]. This expansion does introduce some modeling errors, though within acceptable limits. To reduce this problem, a higher order Padé approximation has been used by Shamsuzzoha and Lee [7,10]. Alternatively, a Taylor expansion can be directly applied to transform an ideal feedback controller into a standard PID-type controller, as suggested by Lee et al. [4]. The performance of the resulting IMC-PID controller is largely dependent on how closely the PID controller approximates an ideal controller equivalent to the IMC controller. It also depends on the structure of the IMC filter. Many methods for approximating an ideal controller to a PID controller have been discussed, but most are case dependent. Few unified approaches to PID controller design that can be employed for all typical time-delay processes have been fully achieved.

In this work, PID filter controllers closely approximating ideal feedback controllers are obtained by using directly high order Padé approximations, since those of previous works only indirectly used Padé approximations in terms of the time delay part. The study is focused on the design of PID controllers cascaded with a lead-lag filters to fulfill various control purposes; tuning rules should be simple, of analytical form, model-based, and easy to implement in practice with excellent performance for both regulatory and servo problems. Several case studies are reported to demonstrate the simplicity and effectiveness of the proposed method compared with several other prominent design methods. The simulation results confirm that the proposed method can afford robust PID filter controllers for both disturbance rejection and set-point tracking.

GENERALIZED IMC APPROACH FOR PID CONTROLLER DESIGN

Consider the standard block diagrams of the feedback control

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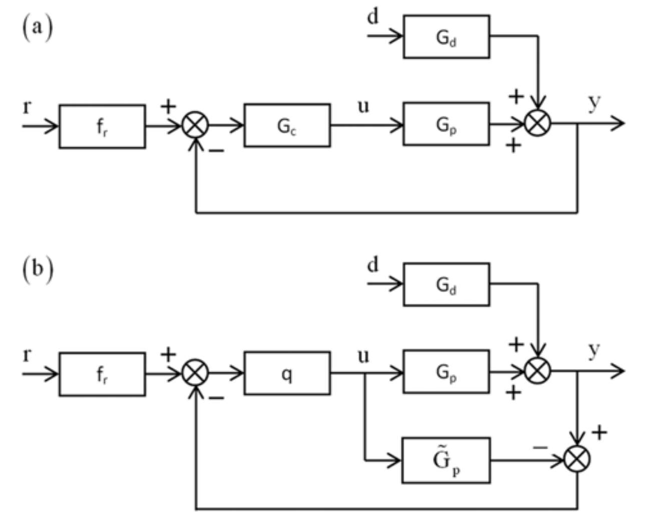

Fig. 1. Block diagram of feedback control strategies. (a) Classical feedback control. (b) Internal model control.

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

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

IMC parameterization [3] leads to the process model, $\tilde{G}_P(s)$, being 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), and $p_A(s)$ the portion not inverted by the controller (it is the non-minimum phase that may include dead time and/or right half plane zeros chosen to be all-pass). The requirement that $p_A(0)=1$ is necessary for the controlled variable to track its set-point with no off-set.

The IMC controller can then be designed as:

$$q(s)=p_m^{-1}(s)f(s). \tag{3}$$

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

$$f(s)=\frac{\Sigma_{i=1}^{m}\beta_i s^i+1}{(\lambda s+1)^n}, \tag{4}$$

where λ is an adjustable parameter that can be used to trade performance and robustness off against each other. The integer n is selected to be large enough for the IMC controller proper. The parameter β_i is determined so as to cancel poles near zero in $G_d(s)$:

$$1-G_P(s)q(s)|_{s=z_{d1},z_{d2},\ldots,z_{dm}}=\left|1-\frac{p_A(s)(\Sigma_{i=1}^{m}\beta_i s^i+1)}{(\lambda s+1)^n}\right|_{s=z_{d1},z_{d2},\ldots,z_{dm}}=0 \tag{5}$$

Substituting Eq. (4) into Eq. (3), gives the IMC controller as:

$$q(s)=p_m^{-1}(s)\frac{(\Sigma_{i=1}^{m}\beta_i s^i+1)}{(\lambda s+1)^n} \tag{6}$$

Substituting Eq. (6) into Eq. (1) allows the closed-loop transfer functions for the desired set-point and the disturbance responses to be respectively simplified as follows:

$$\frac{y(s)}{r(s)}=\frac{p_A(s)(\Sigma_{i=1}^{m}\beta_i s^i+1)}{(\lambda s+1)^n} \tag{7}$$

$$\frac{y(s)}{d(s)}=\left[1-\frac{p_A(s)(\Sigma_{i=1}^{m}\beta_i s^i+1)}{(\lambda s+1)^n}\right]G_d(s) \tag{8}$$

The ideal feedback controller, $G_c(s)$, that yields the desired loop responses in Eq. (7) and Eq. (8) can be constituted as:

$$G_c(s)=\frac{q(s)}{1-\tilde{G}_P(s)q(s)} \tag{9}$$

Therefore, the ideal feedback controller for achieving the desired loop response is obtained by:

$$G_c(s)=\frac{p_m^{-1}(s)(\Sigma_{i=1}^{m}\beta_i s^i+1)}{(\lambda s+1)^n-p_A(s)(\Sigma_{i=1}^{m}\beta_i s^i+1)} \tag{10}$$

As indicated by Eq. (10), the numerator expression $(\Sigma_{i=1}^{m}\beta_i s^i+1)$ may cause an unreasonable overshoot of the servo response. To overcome this, a suitable set-point filter has to be added. Since the controller given by Eq. (10) does not have the standard form of a PID filter-type controller, it is necessary to find a PID-filter controller that approximates the ideal feedback controller most closely.

DESIGN OF A PID CONTROLLER CASCADED WITH A LEAD-LAG FILTER

The ideal feedback controller, $G_c(s)$, is converted to a standard PID controller as follows:

Because $G_c(s)$ has an integral term,

$$G_c(s)=\frac{f(s)}{s}. \tag{11}$$

where:

$$f(s)=G_c(s)s=\left\{\frac{p_m^{-1}(s)(\Sigma_{i=1}^{m}\beta_i s^i+1)}{(\lambda s+1)^n-p_A(s)(\Sigma_{i=1}^{m}\beta_i s^i+1)}\right\}s \tag{12}$$

In this work, a 3/1 Padé expansion is employed because it is sufficiently precise to afford barely any loss of accuracy from the controller structure.

Expanding $G_c(s)$ by the 3/1 Padé approximation in s gives:

$$G_c(s)=\frac{1}{s}(f_0+f_1s+f_2s^2+f_3s^3+f_4s^4+\ldots)$$
$$\cong\frac{1}{s}\frac{p_3s^3+p_2s^2+p_1s+p_0}{q_1s+q_0}, \tag{13}$$

where:

$$f_0=f(0),\ f_1=f'(0),\ f_2=f''(0)/2,\ f_3=f'''(0)/6,\ f_4=f^{(4)}(0)/24, \tag{14}$$

and

$$p_0=f_0,\ p_1=-f_0\left(\frac{f_4}{f_3}\right)+f_1,\ p_2=-f_1\left(\frac{f_4}{f_3}\right)+f_2,$$

$$p_3=-f_2\left(\frac{f_4}{f_3}\right)+f_3,\ q_0=1,\ q_1=-\left(\frac{f_4}{f_3}\right) \tag{15}$$

The above expansion can be succinctly interpreted as a standard PID controller cascaded with a lead-lag filter:

$$G_c(s)=K_c\left(1+\frac{1}{\tau_I s}+\tau_D s\right)\frac{as+1}{bs+1}$$
$$=\frac{1}{s}\frac{K_c\tau_D as^3+K_c(a+\tau_D)s^2+K_c\left(1+\frac{a}{\tau_I}\right)s+\left(\frac{K_c}{\tau_I}\right)}{(bs+1)} \tag{16}$$

A comparison of Eq. (13) and Eq. (16) yields tuning rules of the proportional, integral, and derivative terms of the proposed PID controller:

$$K_c=p_1-ap_0=f_1-f_0(a-b), \tag{17}$$

$$\tau_I=\frac{K_c}{p_0}=\frac{K_c}{f_0}, \tag{18}$$

$$\tau_D=\frac{p_3}{aK_c} \tag{19}$$

Here, the filter parameter b in Eq. (16) is:

$$b=q_1=-\left(\frac{f_4}{f_3}\right). \tag{20}$$

Note that for enhanced performance, a value of 0.1b is recommended instead of b [9,11].

The filter parameter a can be calculated as the positive root of the cubic equation:

$$a^3p_0-a^2p_1+ap_2-p_3=0 \tag{21}$$

Similar to Eq. (7), the lead term (βs+1) can cause excessive overshoots of the set-point response. This can be overcome by adding a suitable set-point filter, $f_r(s)$. For the first- and second-order process models, the set-point filters to enhance servo responses are Eq. (22) and Eq. (23), respectively:

$$f_r(s)=\frac{\gamma\beta s+1}{\beta s+1}, \tag{22}$$

$$f_r(s)=\frac{\gamma\tau_1 s+1}{(\tau_1\tau_D s^2+\tau_1 s+1)}, \tag{23}$$

where $0\le\gamma\le1$.

Online adjustment of γ is required to obtain the desired speed of the set-point response.

PROPOSED TUNING RULES FOR TYPICAL TIME-DELAY MODELS

This section proposes tuning rules for several typical time-delay process models.

1. First-order Plus Dead Time (FOPDT) Process Model

One of the most widely used models is the FOPDT process model:

$$G_P(s)=\frac{Ke^{-\theta s}}{\tau s+1} \tag{24}$$

where K, τ, and θ represent process gain, time constant, and time delay, respectively.

For the 2DOF control structure, the IMC filter can take the following form:

$$f(s)=\frac{\beta s+1}{(\lambda s+1)^2} \tag{25}$$

This IMC filter form has been considered by several researchers [5,10,12]. Accordingly, the ideal feedback controller follows:

$$G_c(s)=\frac{(\tau s+1)(\beta s+1)}{K[(\lambda s+1)^2-e^{-\theta s}(\beta s+1)]} \tag{26}$$

The lead-lag filter parameters b and a can be found from Eq. (20) and Eq. (21), respectively. Tuning rules for the proposed PID controller can also be obtained by considering Eq. (17), Eq. (18), and Eq. (19).

The value of the extra degree of freedom, β, can be determined by compensating the open-loop pole at $s=-1/\tau$. According to Eq. (5), it is:

$$\beta=\tau\left[1-\left(1-\frac{\lambda}{\tau}\right)^2e^{-\theta/\tau}\right] \tag{27}$$

This equation has also been used by several researchers.

2. Integrator Plus Time Delay Model

This model is also applicable to delayed integrating processes (DIPs), which can be reasonably modeled by considering the integrator as a stable pole near zero for the aforementioned IMC procedure to be applicable to an FOPDT, since the term β disappears at s=0. As discussed by Lee et al. [12], the controller resulting from a model with a stable pole near zero can give more robust closed-loop responses than those based on models with an integrator or an unstable pole near zero. Therefore, a DIP can be approximated to an FOPDT as follows:

$$G_p(s)=G_D(s)=\frac{Ke^{-\theta s}}{s}=\frac{Ke^{-\theta s}}{s+\frac{1}{\psi}}=\frac{\psi Ke^{-\theta s}}{\psi s+1}, \tag{28}$$

where ψ is a sufficiently large arbitrary constant. The IMC filter structure for the DIP model is identical to that for the FOPDT model: $f(s)=(\beta s+1)/(\lambda s+1)^2$. Consequently, the IMC controller becomes:

$$q(s)=(\psi s+1)(\beta s+1)/K\psi(\lambda s+1)^2 \tag{29}$$

And the ideal feedback controller is:

$$G_c(s)=(\psi s+1)(\beta s+1)/K\psi[(\lambda s+1)^2-e^{-\theta s}(\beta s+1)] \tag{30}$$

Thus, the ideal feedback controller for the DIP model can be approximated as that for the FOPDT model. The PID controller tuning rules used for the FOPDT model are applicable to the DIP model after a simple modification: the process gain and time constant are replaced by $K\psi$ and ψ, respectively. β can be obtained as:

$$\beta=\psi\left[1-\left(1-\frac{\lambda}{\tau}\right)^2e^{-\theta/\psi}\right] \tag{31}$$

3. First-order Delayed Unstable Process (FODUP) Model

The unstable FOPDT process model is frequently used in the chemical industry:

$$G_P(s)=G_D(s)=\frac{Ke^{-\theta s}}{\tau s-1} \quad (32)$$

The IMC filter structure exploited here is also identical to that for the FOPDT process model, i.e., $f(s)=(\beta s+1)/(\lambda s+1)^2$. Therefore, the IMC controller becomes:

$$q(s)=(\tau s-1)(\beta s+1)/K(\lambda s+1)^2 \quad (33)$$

From this:

$$G_c(s)=(\tau s-1)(\beta s+1)/K[(\lambda s+1)^2-e^{-\theta s}(\beta s+1)] \quad (34)$$

Hence, the above-mentioned strategy can simply generate the controller. The value of β can be found as:

$$\beta=\tau\left[\left(1+\frac{\lambda}{\tau}\right)^2 e^{\theta/\tau}-1\right] \quad (35)$$

This equation has been considered by other researchers [12,13]. Second-order plus dead time (SOPDT) process model.

The most widely used approximate model for chemical processes is the SOPDT model:

$$G_P(s)=G_D(s)=\frac{Ke^{-\theta s}}{(\tau_1 s+1)(\tau_2 s+1)} \quad (36)$$

The IMC filter structure is suggested as $f(s)=(\beta_2 s^2+\beta_1 s+1)/(\lambda s+1)^4$, a structure considered by several authors [7,12]. Accordingly, the IMC controller is given by:

$$q(s)=(\tau_1 s+1)(\tau_2 s+1)(\beta_2 s^2+\beta_1 s+1)/K(\lambda s+1)^4 \quad (37)$$

And the ideal feedback controller is:

$$G_c(s)=(\tau_1 s+1)(\tau_2 s+1)(\beta_2 s^2+\beta_1 s+1)/K[(\lambda s+1)^4-e^{-\theta s}(\beta_2 s^2+\beta_1 s+1)] \quad (38)$$

The resulting PID controller tuning rules can be obtained by considering the above procedure. β_1 and β_2 can be calculated to cancel out the poles at τ_1 and τ_2 by solving the following equation:

$$1-\left.\frac{(\beta_2 s^2+\beta_1 s+1)e^{-\theta s}}{(\lambda s+1)^4}\right|_{s=1/\tau_1,1/\tau_2}=0 \quad (39)$$

Thus:

$$\beta_1=\frac{\tau_1^2\left[\left(1-\frac{\lambda}{\tau_1}\right)^4 e^{-\theta/\tau_1}-1\right]-\tau_2^2\left[\left(1-\frac{\lambda}{\tau_2}\right)^4 e^{-\theta/\tau_2}-1\right]}{(\tau_1-\tau_2)}, \quad (40)$$

$$\beta_2=\tau_2^2\left[\left(1-\frac{\lambda}{\tau_2}\right)^4 e^{-\theta/\tau_2}-1\right]+\beta_1\tau_2 \quad (41)$$

Eq. (40) and Eq. (41) have been widely used to design 2DOF controllers for SOPDT process models.

4. First-order Delayed Integrating Process (FODIP) Model

The FODIP process model can be represented as:

$$G_P(s)=G_D(s)=\frac{Ke^{-\theta s}}{s(\tau s+1)}=\frac{\psi Ke^{-\theta s}}{(\psi s+1)(\tau s+1)} \quad (42)$$

Thus, its ideal feedback controller can be approximated as that of the SOPDT process model. The PID controller tuning rules obtained for the SOPDT process model can also be used for the FODIP process model after a simple modification: replacing the process gain (K) and time constants (τ_1 and τ_2) in Eq. (38) with $K\psi$, ψ, and τ, respectively. The values of β_1 and β_2 are easily obtained from the modification of Eq. (40) and Eq. (41), where τ_1 and τ_2 are replaced by ψ and τ.

5. Second-order Delayed Unstable Process (SODUP) Model

5-1. SODUP Model with One Unstable Pole

The transfer function of the process model is:

$$G_P(s)=G_D(s)=\frac{Ke^{-\theta s}}{(\tau_1 s-1)(\tau_2 s+1)} \quad (43)$$

The IMC filter structure can also be chosen as $f(s)=(\beta_2 s^2+\beta_1 s+1)/(\lambda s+1)^4$, making the IMC controller:

$$q(s)=(\tau_1 s-1)(\tau_2 s+1)(\beta_2 s^2+\beta_1 s+1)/K(\lambda s+1)^4 \quad (44)$$

Therefore:

$$G_c(s)=(\tau_1 s-1)(\tau_2 s+1)(\beta_2 s^2+\beta_1 s+1)/K[(\lambda s+1)^4-e^{-\theta s}(\beta_2 s^2+\beta_1 s+1)] \quad (45)$$

The resulting PID controller tuning rules can be designed by the above procedure for the SOPDT in terms of changing the sign of τ_1.

5-2. SODUP Model with Two Unstable Poles

On the basis of the above design procedure, the process can be representatively modeled as:

$$G_P(s)=G_D(s)=\frac{Ke^{-\theta s}}{(\tau_1 s-1)(\tau_2 s-1)} \quad (46)$$

The IMC filter is $f(s)=(\beta_2 s^2+\beta_1 s+1)/(\lambda s+1)^4$. The IMC controller is then formulated by:

$$q(s)=(\tau_1 s-1)(\tau_2 s-1)(\beta_2 s^2+\beta_1 s+1)/K(\lambda s+1)^4 \quad (47)$$

From this:

$$G_c(s)=(\tau_1 s-1)(\tau_2 s-1)(\beta_2 s^2+\beta_1 s+1)/K[(\lambda s+1)^4-e^{-\theta s}(\beta_2 s^2+\beta_1 s+1)] \quad (48)$$

The resulting PID controller tuning rules can be calculated using the above design principle for the SOPDT by changing the signs of τ_1 and τ_2.

The proposed method can also be applied directly to the design of controllers for processes with negative or positive zeros, $G_P(s)=(\tau_a s\pm 1)Ke^{-\theta s}/(\tau_1 s\pm 1)(\tau_2 s\pm 1)$, without any reduction of model order.

PERFORMANCE AND ROBUSTNESS MEASUREMENTS

1. Integral Absolute Error (IAE) Criteria

To evaluate closed-loop performance, the IAE criterion is considered here for both disturbance rejection and set-point tracking:

$$IAE=\int_0^\infty |e(t)|dt \quad (49)$$

It should be as small as possible.

2. Overshoot

Responses overshoot if they exceed the ultimate value following a step change in disturbance or set-point.

3. Maximum Sensitivity (Ms) Criterion

The robustness of a control system can be evaluated from the peak value of the sensitivity function Ms, which has many useful physical interpretations [14]. Ms is defined as the inverse of the shortest distance from the Nyquist curve of the loop transfer function to the critical point (−1, 0):

$$Ms = \max_{0\le\omega\le\infty}\left|\frac{1}{(1+G_p(j\omega)G_c(j\omega))}\right| \quad (50)$$

For a fair comparison, the model-based controllers should be tuned by adjusting λ so that the Ms values are identical, meaning that all comparative controllers are designed to have the same level of robustness in terms of maximum sensitivity.

4. Total Variation (TV)

TV is a measure of the smoothness of a signal and can be used to evaluate the required control effort. It is computed from the total variation of the manipulated variable by considering the sum of all moves up and down:

$$TV = \sum_{i=1}^{\infty}|u_{i+1} - u_i| \quad (51)$$

SIMULATION STUDY

The effectiveness of the proposed PID tuning rules is demonstrated in several illustrative examples.

1. Example 1 - a FOPDT Process

The following FOPDT process was introduced by Chien et al. [15]. It is an important viscosity loop in a polymerization process with a large open loop time constant and dead time. The process transfer function is:

$$G_p(s) = G_d(s) = \frac{3e^{-10s}}{100s+1} \quad (52)$$

Shamsuzzoha and Lee [10] previously confirmed the superiority of their method over that of Chien et al. [15] for this polymerization process. Therefore, in this simulation study, the proposed PID controller is compared with the controller of Shamsuzzoha and Lee [10], as well as the PID controllers of Horn et al. [5] and Rivera et al. [2]. For a fair comparison, all controllers are tuned to have the same level of robustness by measuring the Ms value. The closed-loop time constant, λ_i, is adjusted to obtain Ms=2.62 in each case.

The resulting controller parameters, together with performance and robustness indices calculated for the foreknown methods, are in Table 1. A load step change of −1.0 is introduced into the load disturbance and the corresponding simulation results are shown in Fig. 2. The figure and table show that the proposed controller affords superior closed-loop performance with faster and better-balanced responses than the other controllers in terms of disturbance rejection.

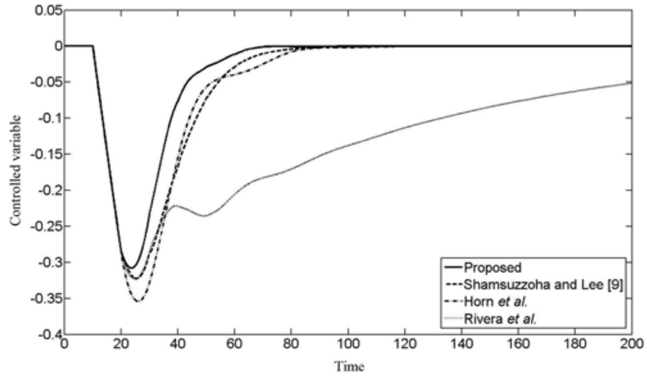

Fig. 2. Simulation results of PID controllers for unit step disturbance (example 1).

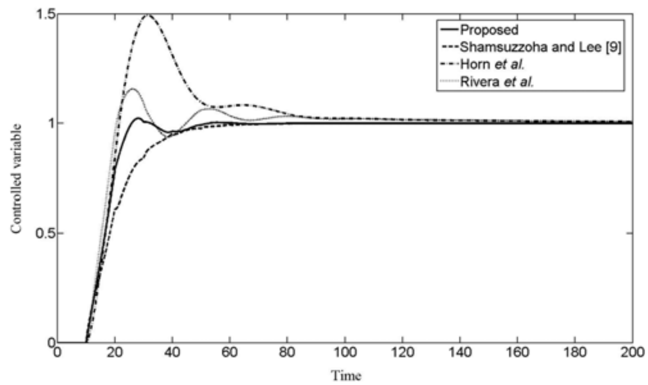

Fig. 3. Simulation results of PID controllers for unit step set-point change (example 1).

The controlled variable responses resulting from unit step changes in the set-point are also shown in Fig. 3. Under the one-degree-of-freedom (1DOF) control structure, any controller achieving good disturbance rejection essentially gives a significant overshoot in set-point response. To overcome this, the 2DOF control structure is commonly used. Consequently, the set-point filter used for the set-point response has a clear benefit. Therefore, a 2DOF controller with set-point filter is used in each case, except for the method of Rivera et al. [2]. To obtain an enhanced set-point response, this method has

Table 1. PID controller parameters and performance matrix for example 1

Tuning methods	K_C	τ_I	τ_D	λ	Ms	Set-point			Disturbance		
						IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed[a]	1.215	7.969	2.434	6.768	2.62	17.97	0.025	5.885	6.67	0.312	2.706
Shamsuzzoha and Lee [10][b]	0.571	5.0	1.667	8.973	2.62	20.89	0.0	14.591	8.77	0.323	3.441
Horn et al.[c]	11.362	105.0	4.762	9.440	2.62	28.57	0.513	11.184	9.58	0.366	3.185
Rivera et al.[d]	3.286	105.0	4.762	0.650	2.62	20.84	0.157	10.914	32.22	0.323	2.314

[a] a=21.351, b=3.708, γ=0.30, $f_r(s)=(6.405s+1)/(21.351s+1)$

[b] a=25.026, b=1.154, γ=0.30, $f_r(s)=(7.058s+1)/(25.026s+1)$

[c] a=25.799, b=101.446, c=144.640, d=0

[d] b=0.305

Noted: the controller forms of Horn et al.'s and Rivera et al.'s methods are $K_c\left(1+\frac{1}{\tau_I s}+\tau_D s\right)\frac{ds^2+as+1}{cs^2+bs+1}$ and $K_c\left(1+\frac{1}{\tau_I s}+\tau_D s\right)\frac{1}{bs+1}$, respectively

Table 2. Robustness analysis for example 1

Tuning methods	+10%						−10%					
	Set-point			Disturbance			Set-point			Disturbance		
	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed method	20.11	0.141	6.633	6.73	0.339	3.401	17.93	0.024	5.964	6.60	0.278	2.638
Shamsuzzoha and Lee [10]	20.63	0.0	14.99	8.77	0.351	3.748	21.27	0.0	14.255	8.78	0.294	3.205
Horn et al.	33.47	0.645	13.585	10.43	0.404	3.858	26.38	0.364	9.252	9.29	0.340	2.630
Rivera et al.	23.29	0.265	12.083	32.22	0.351	2.666	18.02	0.050	10.03	32.22	0.294	2.054

been previously suggested for use with a 1DOF controller with a conventional lag filter; therefore, it is used here without modification. For the proposed method and that of Shamsuzzoha and Lee [10], γ in the set-point filter is selected to be 0.3. Fig. 3 shows that the proposed method, together with that of Shamsuzzoha and Lee [10], performs better than the other methods. However, the PID controller of Shamsuzzoha and Lee [10] affords the largest value of TV due to the dominant lead term in the controller filter.

The robust performance of the proposed method is demonstrated in another simulation study, where perturbation uncertainties of ±10% are introduced to the process gain, time constant, and time delay in the worst direction and assuming the actual processes as $G_p(s)=3.3e^{-11s}/110s+1$ and $G_p(s)=2.7e^{-9s}/90s+1$, respectively. The controller settings are those provided for the nominal process. Note that the robust performance has been investigated by inserting the perturbation uncertainty to each process parameter for both disturbances and set-point changes. The simulation results for all the tuning rules are in Table 2 for the set-point and disturbance rejection problems, respectively; they confirm that the controller settings of the proposed method provide more robust performance than those of the other methods for both disturbances and set-point changes.

2. Example 2 - a DIP Process

The following process model [16] is considered. It can be reasonably approximated to the FOPDT process model as follows:

$$G_p(s)=G_d(s)=\frac{0.2e^{-7.4s}}{s}=\frac{20e^{-7.4s}}{100s+1} \tag{53}$$

In this simulation study, the constant ψ is arbitrarily selected as 100. The performance of the proposed method is compared with those of the aforementioned design methods. λ_i is adjusted to obtain Ms=2.40 in each case. Figs. 4 and 5 show the closed-loop time responses for disturbance rejection and set-point, respectively. The proposed controller shows a fast, well-balanced response with minimum integral IAE values, whereas that of Shamsuzzoha and Lee

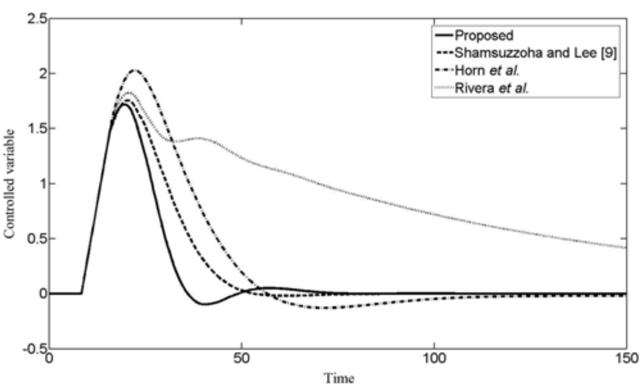

Fig. 4. Simulation results of PID controllers for unit step disturbance (example 2).

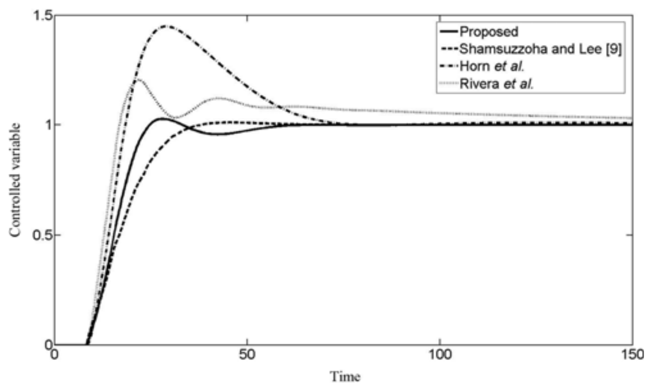

Fig. 5. Simulation results of PID controllers for unit step set-point change (example 2).

Table 3. PID controller parameters and performance matrix for example 2

Tuning methods	K_C	τ_I	τ_D	λ	Ms	Set-point			Disturbance		
						IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed[a]	0.254	7.495	1.972	6.072	2.40	15.53	0.028	0.991	26.95	1.683	2.814
Shamsuzzoha and Lee [10][b]	0.107	3.70	1.233	7.010	2.40	17.12	0.012	1.523	35.23	1.755	2.956
Horn et al.[c]	2.568	103.70	3.568	8.065	2.40	24.53	0.561	1.838	53.98	2.028	2.269
Rivera et al.[d]	0.613	103.70	3.568	1.060	2.40	22.80	0.204	1.852	169.50	1.824	2.004

[a] a=18.064, b=4.533, γ=0.15, $f_r(s)=(2.688s+1)/(17.916s+1)$
[b] a=19.697, b=0.892, γ=0.15, $f_r(s)=(2.955s+1)/(19.697s+1)$
[c] a=21.511, b=101.192, c=119.195
[d] b=0.464

Table 4. Robustness analysis for example 2

Tuning methods	+10%						−10%					
	Set-point			Disturbance			Set-point			Disturbance		
	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed method	18.12	0.127	1.589	37.81	2.014	5.225	15.88	0.025	0.694	27.32	1.428	2.193
Shamsuzzoha and Lee [10]	16.74	0.0	3.075	34.87	2.026	3.755	18.67	0.039	1.409	37.23	1.511	2.330
Horn et al.	27.39	0.782	2.619	42.92	2.321	3.582	23.98	0.392	1.526	42.41	1.706	1.858
Rivera et al.	24.64	0.388	2.532	169.50	2.107	3.032	23.27	0.108	1.463	169.5	1.572	1.425

[10] shows a slow response with a longer settling time. The controllers of Horn et al. [5] and Rivera et al. [2] give large overshoots. The resulting controller parameters, together with their performances, and robustness indices, are summarized in Table 3. The results show that the proposed method affords good performance for both disturbance rejection and set-point tracking.

In the robustness study, the controllers are evaluated by considering the worst cases under simultaneous ±10% perturbation uncertainties in all three process parameters. The simulation results for plant-model mismatch are in Table 4. The proposed method consistently affords strong robust performance both for disturbances and set-point changes.

3. Example 3 - a FODUP Process

The following FODUP model is considered:

$$G_p(s) = G_d(s) = \frac{e^{-0.4s}}{s-1} \tag{54}$$

It has been extensively studied by several authors. Shamsuzzoha and Lee [7] demonstrated the superiority of their method over those of Liu et al. [6], Lee et al. [12], and Tan et al. [17], and have also shown the significant improvement of their method over a number of other methods, including those of De Paor and O'Malley [18], Rotstein and Lewin [19], and Huang and Chen [20]. Therefore, the proposed method is compared with those of Shamsuzzoha and Lee [7] and Lee et al. [12]. In each case, the adjustable parameter λ is selected to obtain the same degree of robustness through the Ms value.

Figs. 6 and 7 show the disturbance and set-point responses afforded by each of the methods, respectively. The proposed method is shown to perform well compared with the other methods. The controller characteristics summarized in Tables 5 and 6 confirm the improvement in the performance of the proposed method.

A perturbation uncertainty of ±10% is simultaneously introduced to all three process parameters to evaluate the controllers' robustness. The simulation results in Table 6 indicate that the proposed PID controller provides improved robust performance both in terms

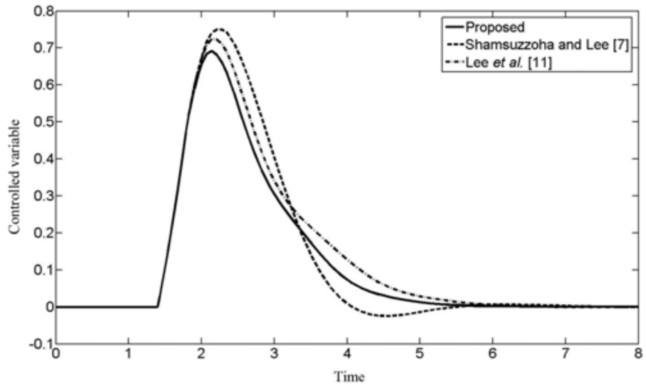

Fig. 6. Simulation results of PID controllers for unit step disturbance (example 3).

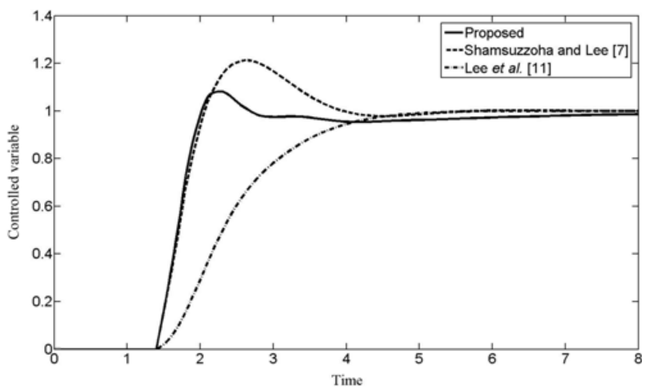

Fig. 7. Simulation results of PID controllers for unit step set-point change (example 3).

Table 5. PID controller parameters and performance matrix for example 3

Tuning methods	K_C	τ_I	τ_D	λ	Ms	Set-point			Disturbance		
						IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed[a]	0.404	0.386	0.104	0.50	2.85	0.898	0.081	3.961	0.956	0.692	3.360
Shamsuzzoha and Lee [8][b]	0.266	0.267	0.100	0.305	2.85	0.967	0.214	3.385	1.045	0.751	3.707
Lee et al. [12][c]	2.526	2.752	0.150	0.552	2.85	1.505	0.00	2.006	1.093	0.725	3.486

[a] a=2.357, b=0.224, γ=0.3, $f_r(s)=(0.97s+1)/(2.772s+1)$
[b] a=2.316, b=0.142, γ=0.3, $f_r(s)=(0.811s+1)/(2.316s+1)$
[c] $f_r(s)=1/(2.594s+1)$

Table 6. Robustness analysis for example 3

Tuning methods	+10%						−10%					
	Set-point			Disturbance			Set-point			Disturbance		
	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed method	1.060	0.180	4.601	0.956	0.741	3.814	0.831	0.059	3.362	0.999	0.643	3.291
Shamsuzzoha and Lee [8]	1.027	0.244	3.847	1.034	0.795	4.033	1.006	0.228	3.490	1.142	0.716	3.622
Lee et al. [12]	1.604	0.00	1.981	1.089	0.773	4.128	1.450	0.019	2.102	1.134	0.679	3.306

of disturbance rejection and set-point tracking.

4. Example 4 - a FODIP Process

The FODIP process studied by Zhang et al. [21] and Shamsuzzoha and Lee [9] is considered:

$$G_p(s)=G_d(s)=\frac{e^{-4s}}{s(4s+1)} \tag{55}$$

The proposed PID controller is compared with those of Shamsuzzoha and Lee [9] and Zhang et al. [21]. Each controller is tuned by adjusting their respective λ such that Ms=3.83. For both the proposed method and that of Shamsuzzoha and Lee [9], the controllers are designed by considering the above process as: $G_p(s)=100e^{-4s}/(100s+1)(4s+1)$, where the arbitrary constant ψ=100. Figs. 8 and 9 show the output responses of each tuning method for disturbance rejection and set-point tracking, respectively. The proposed method shows the fastest settling time and a small overshoot. The method of Shamsuzzoha and Lee [9] settles next quickest, while Zhang et al.'s [21] method gives significant overshoot and oscillation that requires a long time to settle. The controller setting parameters for each method are listed in Table 7; it also shows the advantages of

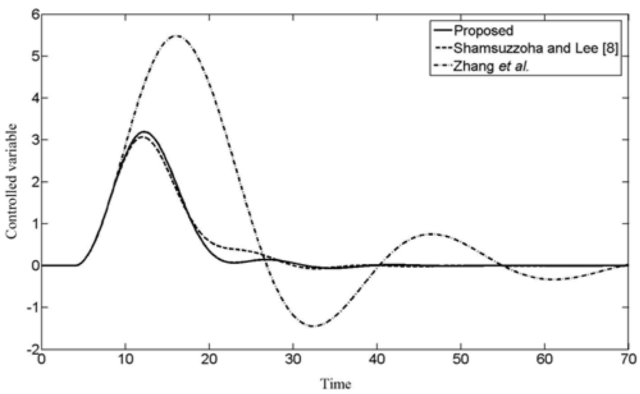

Fig. 8. Simulation results of PID controllers for unit step disturbance (example 4).

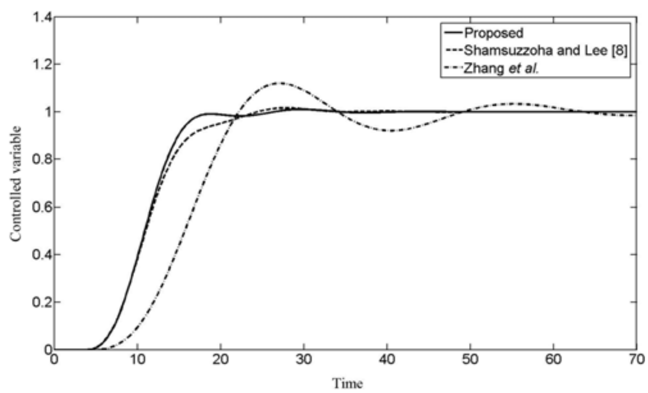

Fig. 9. Simulation results of PID controllers for unit step set-point change (example 4).

Table 7. PID controller parameters and performance matrix for example 4

Tuning methods	K_C	τ_I	τ_D	λ	Ms	Set-point			Disturbance		
						IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed[a]	0.386	11.070	2.507	1.905	3.83	11.18	0.010	0.5667	29.29	3.192	3.974
Shamsuzzoha and Lee [9][b]	0.388	11.473	2.643	1.942	3.83	11.68	0.016	1.019	30.35	3.069	8.849
Zhang et al.[c]	0.246	15.122	2.942	2.374	3.83	17.64	0.119	0.351	92.8	5.481	4.165

[a] a=2.022, b=0.129, γ=0, $f_r(s)=1/(27.753s^2+11.070s+1)$
[b] a=2.0, b=0.0392, γ=0, $f_r(s)=1/(30.306s^2+11.473s+1)$
[c] a=0, b=0.218, γ=0, $f_r(s)=1/(44.489s^2+15.122s+1)$

Table 8. Robustness analysis for example 4

Tuning methods	+10%						−10%					
	Set-point			Disturbance			Set-point			Disturbance		
	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed method	12.72	0.118	0.845	40.25	3.525	5.698	11.43	0.019	0.471	29.44	2.854	3.464
Shamsuzzoha and Lee [9]	12.00	0.043	1.267	34.06	3.402	10.137	11.85	0.016	0.914	30.47	2.734	8.569
Zhang et al.	11.99	0.218	0.576	146.00	5.861	6.269	15.72	0.040	0.242	69.62	5.094	2.945

the proposed method over the other methods. Table 8 shows performance index values, when ±10% perturbation uncertainty is simultaneously introduced to all three process parameters for worst-case model mismatch. The performance and robustness indices clearly demonstrate the significantly more robust performance of the proposed controller.

The most important factor for robust performance is the value of b. In Shamsuzzoha and Lee's [9] method, robust performance was achieved using a value of 0.1b instead of b. When this is applied to the proposed method, the level of robustness increases, as Ms=3.57. To guarantee a fair comparison, the controller of Shamsuzzoha and Lee [9] is adjusted to have the same degree of robustness, by using λ=2.017; in this case, the resulting controller of the proposed method affords a much enhanced robust performance.

5. Example 5 - a SODUP (One Unstable Pole) Process

The following SOPUP model with one unstable pole was approximated by Huang and Chen [20]:

$$G_p(s) = G_d(s) = \frac{e^{-0.939s}}{(5s-1)(2.07s+1)} \tag{56}$$

In previous research, Lee et al. [12] confirmed the superiority of their method over several other design methods, such as Huang and Chen [20] and Poulin and Pomerleau [22]. Shamsuzzoha and Lee [9] also demonstrated the advantage of their method over that of Rao and Chidambaram [11]. Therefore, the proposed method is compared with both methods to show its effectiveness. To provide a fair comparison, each controller is tuned to the same degree of robustness by adjusting λ. In this example, both the proposed method and that of Shamsuzzoha and Lee [9] employ a value of 0.1b to improve their robust performance.

Unit step changes are introduced to both the load disturbance and set-point. A set-point filter is used in each case to enhance the set-point response without affecting the disturbance response.

The simulation results in Figs. 10 and 11, and Table 9 show that the proposed controller gives better output responses with smaller IAE values than those of the other methods, particularly with respect to disturbance rejection.

To evaluate robustness, perturbation uncertainties of ±10% are simultaneously introduced to all three parameters in the worst direction. The simulation results of model mismatch for each method

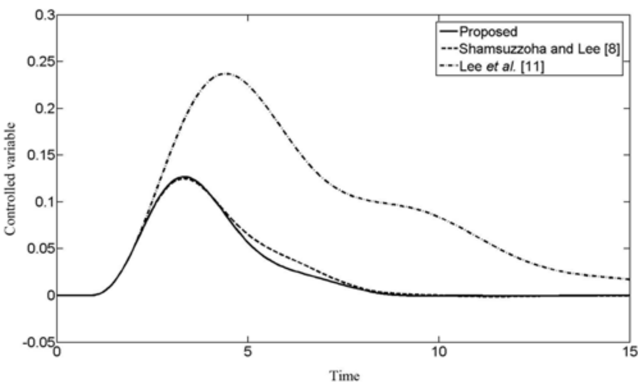

Fig. 10. Simulation results of PID controllers for unit step disturbance (example 5).

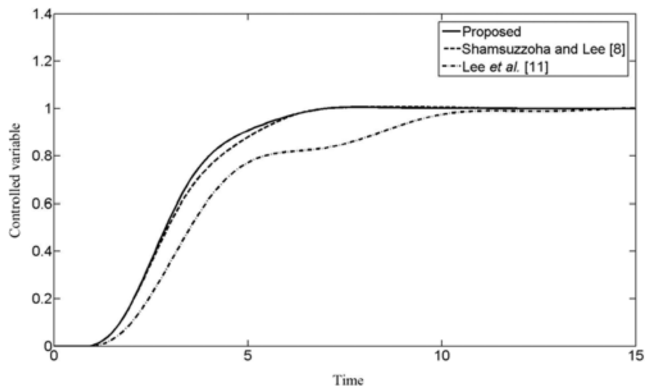

Fig. 11. Simulation results of PID controllers for unit step set-point change (example 5).

Table 9. PID controller parameters and performance matrix for example 5

Tuning methods	K_C	τ_I	τ_D	λ	Ms	Set-point			Disturbance		
						IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed[a]	9.972	3.862	1.122	0.637	3.5	3.116	0.006	13.254	0.390	0.125	4.429
Shamsuzzoha and Lee [9][b]	9.642	3.994	1.438	0.660	3.5	3.222	0.006	12.236	0.419	0.124	4.055
Lee et al. [12][c]	5.620	8.052	1.756	1.650	3.5	4.279	0.006	9.241	1.402	0.236	4.008

[a] a=0.422, b=0.0057, γ=0.10, $f_r(s)=(0.386s+1)/(4.334s^2+3.862s+1)$
[b] a=0.470, b=0.0126, γ=0.10, $f_r(s)=(0.3994s+1)/(4.568s^2+3.994s+1)$
[c] $f_r(s)=1/(5.672s^2+1)$

Table 10. Robustness analysis for example 5

Tuning methods	+10%						−10%					
	Set-point			Disturbance			Set-point			Disturbance		
	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed method	3.175	0.034	16.849	0.420	0.138	4.983	3.173	0.014	16.371	0.395	0.116	5.537
Shamsuzzoha and Lee [9]	3.192	0.007	14.127	0.420	0.137	4.113	3.279	0.014	18.314	0.423	0.114	6.035
Lee et al. [12]	4.275	0.008	9.293	1.410	0.251	3.896	4.303	0.007	10.396	1.401	0.223	4.620

are tabulated in Table 10. The performance and robustness indices clearly demonstrate the advantages of the proposed controller for both disturbance rejection and set-point tracking.

6. Example 6 - a SODUP (Two Unstable Poles) Process

The SODUP process considered below has been studied by a number of authors [6,9,11,12].

$$G_p(s)=G_d(s)=\frac{2e^{-0.3s}}{(3s-1)(s-1)} \quad (57)$$

For this unstable process with two unstable poles, Rao and Chidambaram [11] demonstrated the enhancement of their method over the commonly accepted approach (Liu et al. [6]). Consequently, their enhanced controller is compared with that of the proposed method at the same degree of robustness. Accordingly, the closed-loop time constant, λ_i, is respectively adjusted to 0.35 and 0.64 for the proposed method and that of Rao and Chidambaram [11] to give the same robustness level of Ms=3.1.

Unit step disturbance and step change are introduced to the plant input and set-point (Figs. 12(a) and 12(b), and Figs. 13(a) and 13(b)), and the corresponding simulation results are listed in Table 11. Comparing the output responses and performance indices shows that the proposed controller provides better performance for both disturbance rejection and set-point tracking.

Simulation results when simultaneously assuming perturbation uncertainties of ±10% in all three parameters of the process are summarized in Table 12. The proposed controller performs robustly for both disturbance rejection and set-point tracking with minimum IAE values.

7. Example 7 - a High Order Process with Positive Zero

The following high order process with positive zero was studied by Skogestad [23]:

$$G_p(s)=G_d(s)=\frac{(-s+1)e^{-s}}{(6s+1)(2s+1)^2} \quad (58)$$

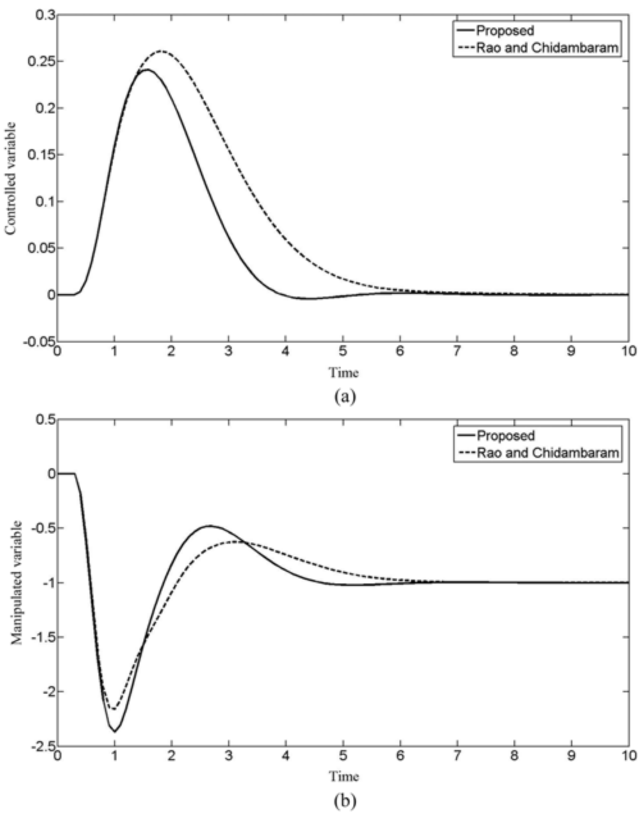

Fig. 12. Simulation results of PID controllers for unit step disturbance (example 6): controlled variable (a); manipulated variable (b).

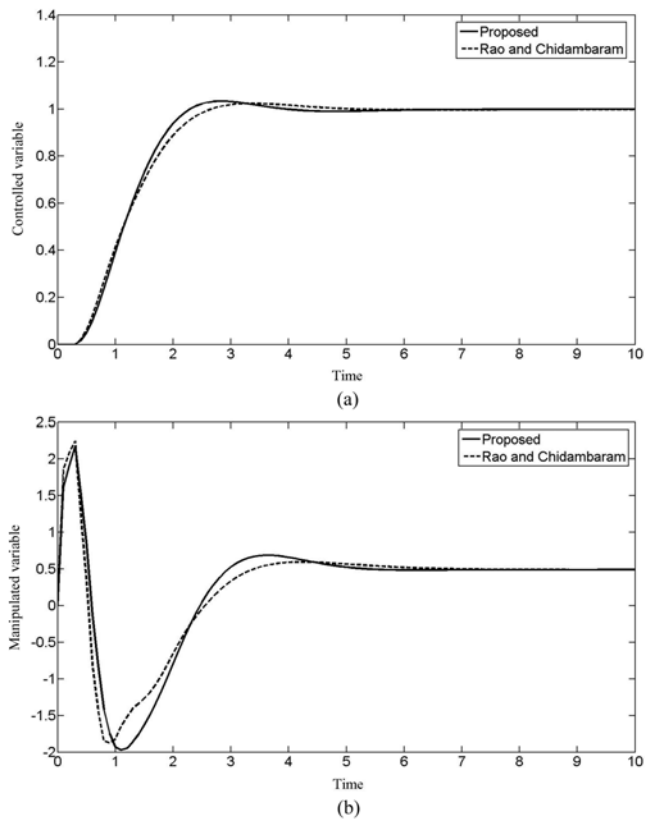

Fig. 13. Simulation results of PID controllers for unit step set-point change (example 6): controlled variable (a); manipulated variable (b).

Table 11. PID controller parameters and performance matrix for example 6

Tuning methods	K_C	τ_I	τ_D	λ	Ms	Set-point			Disturbance		
						IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed[a]	3.567	1.491	1.337	0.350	3.10	1.246	0.034	9.178	0.425	0.241	4.833
Rao and Chidambaram[b]	2.972	1.900	1.614	0.640	3.10	1.270	0.024	8.949	0.639	0.261	4.071

[a] a=0.1384, b=0.00461, γ=0.35, $f_r(s)=(0.522s+1)/(1.993s^2+1.491s+1)$

[b] a=0.150, b=0.0041, a set-point weighting parameter is set as 0.536

Table 12. Robustness analysis for example 6

Tuning methods	+10%						−10%					
	Set-point			Disturbance			Set-point			Disturbance		
	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed method	1.182	0.012	11.485	0.419	0.279	6.428	1.223	0.009	8.527	0.418	0.224	4.452
Rao and Chidambaram	1.243	0.018	10.699	0.640	0.285	4.836	1.261	0.007	9.222	0.639	0.242	3.966

To handle this high order process, the model reduction technique proposed by Skogestad [23] can be used for obtaining a typical process model as follows:

$$G_p(s)=G_d(s)=\frac{e^{-5s}}{(7s+1)} \tag{59}$$

Then, the proposed controller can be obtained by considering the tuning rules for FOPDT model. The proposed method compares fairly with that of Shamsuzzoha and Lee [10]. As can be seen from Figs. 14 and 15, and Table 13, the proposed controller provides superior performances both for disturbance rejection and set-point tracking.

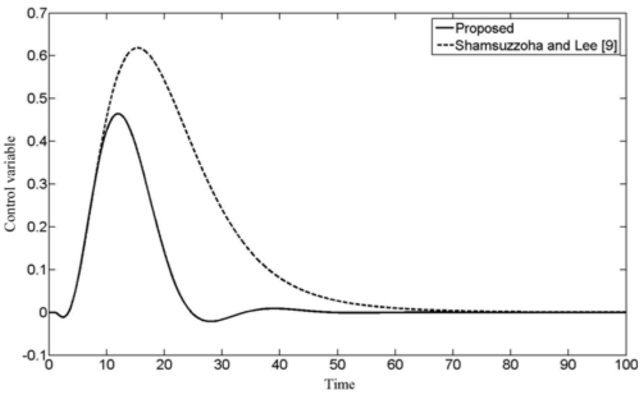

Fig. 14. Simulation results of PID controllers for unit step disturbance (example 7).

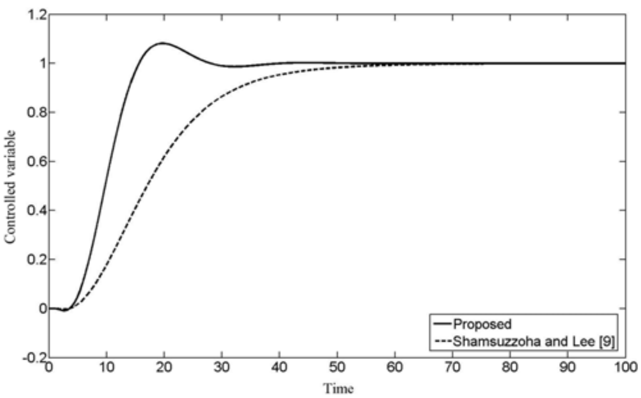

Fig. 15. Simulation results of PID controllers for unit step set-point change (example 7).

DISCUSSION

1. Effect of λ on the Tradeoff between Performance and Robustness

The closed-loop time constant, λ, is an important user-defined tuning parameter for any IMC-based approach, and is usually used to control the tradeoff between performance and robustness. It is necessary to provide guidelines that afford the best performance at a given degree of robustness for the different PID controllers cascaded with lead/lag filters.

Consider the general model of FOPDT:

$$G_p(s)=G_d(s)=\frac{e^{-\theta s}}{s+1} \tag{60}$$

The proposed controller setting is calculated for six values of θ/τ (0.5, 1.0, 1.5, 2.0, 2.5, 3.0) and five different robustness levels of Ms (1.9, 1.95, 2.00, 2.05, 2.10).

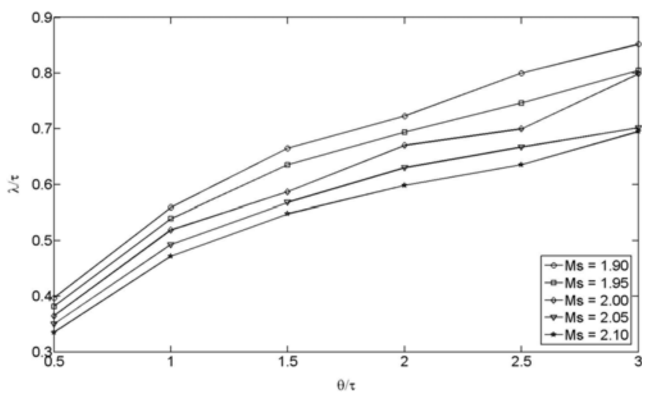

Fig. 16. λ guidelines for FOPDT.

Table 13. PID controller parameters and performance matrix for example 7

Tuning methods	K_C	τ_I	τ_D	λ	Ms	Set-point			Disturbance		
						IAE	Overshoot	TV	IAE	Overshoot	TV
Proposed[a]	2.123	10.867	2.668	3.00	1.84	6.705	0.08	1.955	5.412	0.465	1.544
Shamsuzzoha and Lee [10][b]	0.189	2.5	0.833	7.615	1.84	13.260	0.00	0.874	13.290	0.619	1.023

[a]a=2.203, b=5.250, γ=0.15, $f_r(s)$=(0.733s+1)/(4.885s+1)
[b]a=6.974, b=1.562, γ=0.15, $f_r(s)$=(1.046s+1)/(6.974s+1)

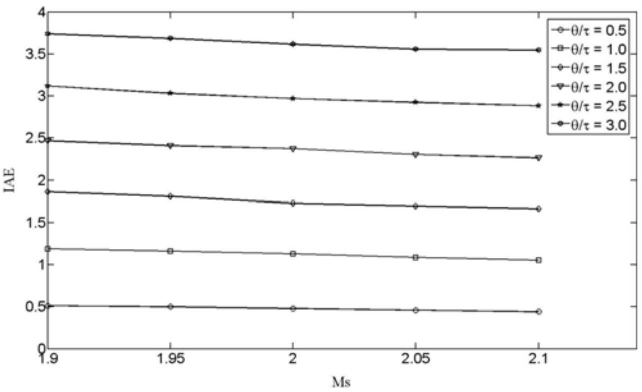

Fig. 17. Ms *vs.* IAE for FOPDT.

Fig. 16 shows the plot of θ/τ *vs.* λ/τ for the above-mentioned FOPDT model, wherein the desired λ are calculated for given Ms values at different θ values. As θ increases, the desired value of λ systematically increases at any level of robustness. The control system exhibits increased robust stability at lower values of Ms. Conversely, the control system exhibits better performance with less robust stability. The figure shows that λ should be chosen smaller for robust control systems as it can reduce robustness and larger λ should be used for control systems that are less robust.

The impact of Ms values on overall closed-loop performance and robustness can be seen in Fig. 17, which plots the Ms and IAE indices (for robustness and performance, respectively) against each other. The figure shows that better closed-loop performance (smaller IAE values) can be achieved when the control system is less robust in stability (larger Ms values) and *vice versa*. Therefore, it is necessary to ascertain the desirable values of Ms and λ to establish a suitable the tradeoff between performance and robustness in any given dynamic model.

2. Effectiveness of the Proposed Method for the Dead-time Dominant Process

Fig. 18 compares the IAE values of the load responses of various PID controllers with a given value of Ms as 2.00 and different values of θ/τ (0.5, 1.5, 3.0, and 4.5). The tuning rules for the proposed method, as well as those for the methods of Shamsuzzoha and Lee [10] and Horn et al. [5], are based on the 2DOF control structure with the same filter: $f(s)=(\beta s+1)/(\lambda s+1)^2$. The tuning rules

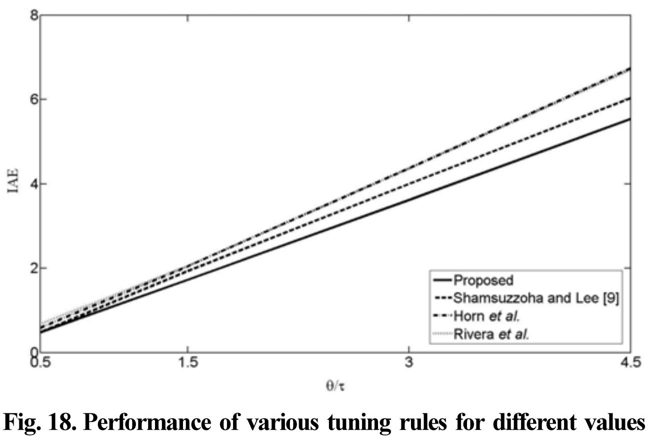

Fig. 18. Performance of various tuning rules for different values of θ/τ.

for the method of Rivera et al. [2] are based on a 1DOF control structure. The figure shows that at a constant Ms value, the smallest IAE value is provided by the proposed method. It is also shows that the IAE gap between the proposed and other methods increases as the θ/τ ratio increases. The load performance of the proposed controller is superior to those of the other methods as the dead-time dominates. The extensive simulation studies for other dynamic models also imply that the proposed controllers have significant advantages for dead-time dominant processes.

CONCLUSIONS

A systematic approach for designing PID controllers cascaded with lead-lag filters is proposed for a variety of processes with time delays. IMC theory provides the basis of the proposed controllers that perform strongly with respect to disturbance rejection. To enhance the set-point response, the proposed method also employs a set-point filter as the 2DOF controller, which has been introduced elsewhere.

The proposed method could cover a broad range of stable, integrating, and unstable processes with time delays using a unified technique. λ guidelines are also provided over a wide range of θ/τ ratios to aid the proper selection of the closed-loop time constant.

The simulation results indicate that the proposed method consistently affords more advanced performance. Faster and better-balanced closed-loop time responses for both disturbance rejection and set-point tracking result when compared with the other methods, since the various controllers are all tuned to have the same degree of robustness in terms of the peak value of the sensitivity function. Robustness was also studied by simultaneously introducing perturbation uncertainties in each of the process parameters to give worst-case mismatch models. The results show that the proposed control systems maintained robust stability in both nominal and plant-model mismatch cases.

ACKNOWLEDGEMENTS

This research was supported by a Yeungnam University grant in 2010.

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