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Design of Cascaded IMC-PID Controller with Improved Filter for Disturbance Rejection

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Abstract: IMC-PID controllers provide good set point tracking but sluggish disturbance rejection, because of introduction of slow process pole by the conventional filter. In many industrial applications disturbance rejection is important than set point tracking. In this paper PID controller with Internal model control tuning method (IMC-PID) with an improved IMC filter is presented for effective disturbance rejection and robust operation of first order process with time delay (FOPTD). The suggested filter eliminates the slow dominant pole. The present study illustrates that the suggested IMC filter provides good disturbance rejection irrespective of where the disturbance enters the process and provides good robustness to model mismatch in terms of sensitivity in comparison with other methods cited in the literature. Simulation study was performed on processes with different θ/τ ratios to show the effectiveness of suggested method by calculating the controller parameters to have same robustness in terms of maximum sensitivity. The closed loop performance was tested using integral error criteria Viz. IAE, ISE, ITAE. The suggested IMC filter provides good disturbance rejection response for process having $\theta/\tau < 1$.

Keywords: IMC; improved filter; disturbance rejection; robustness; sensitivity; integral criteria; FOPTD.

1. Introduction

The most widely used controller in the process industries is Proportional integral derivative (PID) controller, as it can assure satisfactory performances with simple algorithm for a wide range of processes. It is important to note that cost benefit ratio obtained through the PID controller is difficult to achieve by other controllers [1-3]. It is found that 97% of the regulatory controllers use PID algorithm [4]. The Internal Model Control (IMC) provides a progressive, effective, natural, generic, unique, powerful, and simple framework for analysis and synthesis of control system performance [5, 6]. Because of the easiness and improved performance of the IMC based tuning rule, the analytically derived IMC-PI/PID (IMC-PID) tuning methods have attracted the attention of industrial users over the last decade[14]. The well-known IMC-PID tuning rule has the advantage that a clear compromise between closed loop performance and robustness to model uncertainties, is achieved by a only one user-defined tuning parameter,

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which is directly related to the closed-loop time constant[1, 5, 7, 8]. In the IMC-PID tuning methods and direct synthesis (DS), the PID controller parameters are obtained by computing the controller which provides the desired closed loop response [7-13].

Load disturbance rejection is one of the most important issues in the context of process control. IMC-PID controller provides a good set-point tracking but the disturbance response is slow, especially when $\theta/\tau << 1$[6, 9, 12]. For most single loop controllers, disturbance rejection is more important than set-point tracking, a controller design that emphasizes the disturbance rejection is an important design goal [6, 9, 14]. The goal can be achieved by designing the controller for disturbance rejection, rather than set-point tracking, where PID controller cascaded with a filter was suggested in the literature [3, 6-8, 10, 14-16].

The efficiency of the IMC-PID is based on the structure of the IMC filter. In the literature the filter structure was selected to make the IMC controller realizable while satisfying the performance requirements. The efficiency of IMC controller and the close approximation of IMC controller to ideal controller determine the efficiency of the resulting PID controller. Therefore suitable IMC filter structure has to be selected not on the performance of IMC controller but the performance of resulting PID controller.

The PID tuning methods described so far in the literature have used process/plant which are First order plus time delay (FOPTD) and second order plus time delay (SOPTD) [11, 17-20]. It is been observed that the higher order models approximated by FOPTD and/or SOPTD can also fulfill the control objectives in satisfactory manner [2, 17, 18]. This has inspired to use model order reduction scheme for predictive plant model. The present work considers the design of suitable control strategy for disturbance rejection by combining IMC-PID controller with model order reduction. This designed controller is capable of squashing the disturbances irrespective of the position at which the disturbance enters the closed-loop system, capable of handling model mismatches and parameter uncertainties.

The objectives of the present work are

a) Identify the transfer function model/ reduce the higher order model of the process to FOPTD model which will be used as predictive model for IMC structure, using techniques Viz. Sundaresan and Krishnaswamy (S-K) described in [2].
b) Consider IMC-PID cascaded with lead/lag filter structure to optimize the performance of system for load disturbance rejection.
c) Perform robustness analysis by incorporating perturbations into the plant (predictive) model parameters and evaluate performance of the closed loop system in terms of integral error criteria.

2. IMC-PI/PID controller design

Internal model control was introduced by Garcia and Morari [7, 21]; it is characterized as a controller where the process model is explicitly an internal part of the controller. The design process of IMC involves factorizing the predictive plant model $G_M(s)$ as invertible $G_{M-}(s)$ and non-invertible $G_{M+}(s)$ parts as shown in (1) by simple factorization or all pass factorization [5, 7, 8, 10, 16]. The Internal model controller (2) is the inverse of the invertible $G_{M-}(s)$ portion of the plant model $G_M(s)$.

$$G_M(s) = G_{M-}(s)G_{M+}(s) \tag{1}$$

The IMC controller is designed as

$$Q(s) = G_{M-}^{-1}(s)G_f(s) \tag{2}$$

The IMC controller can take the form of ideal feedback controller of Figure 2 or Figure 3 by making small modifications to Figure 1, which can be expressed mathematically in terms of $Q(s)$ and $G_M(s)$ as (3)

$$G_C(s) = \frac{Q(s)}{1 - Q(s)G_M(s)} \tag{3}$$

The controller obtained in (3) does not have the standard PID form, the PID parameters can be obtained by reducing the controller form to the structure that of either a PID controller of (4) or a PID controller cascaded with a low order filter of (5), by performing appropriate approximation of the dead time in the process model.

$$G_C(s) = G_{PID}(s) = K_P\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{4}$$

$$G_C(s) = G_{PID}(s) = K_P\left(1 + \frac{1}{T_i s} + T_d s\right)\left(\frac{ds^2 + cs + 1}{as^2 + bs + 1}\right) \tag{5}$$

The output response $Y(s)$ of the closed loop system for Set point input $R(s)$, load disturbance input $L(s)$ and output load disturbance input $D(s)$ is (6)

$$Y(s) = \frac{G_C(s)G_P(s)}{1 + G_C(s)G_P(s)}R(s) + \frac{1}{1 + G_C(s)G_P(s)}D(s) + \frac{G_P(s)}{1 + G_C(s)G_P(s)}L(s) \tag{6}$$

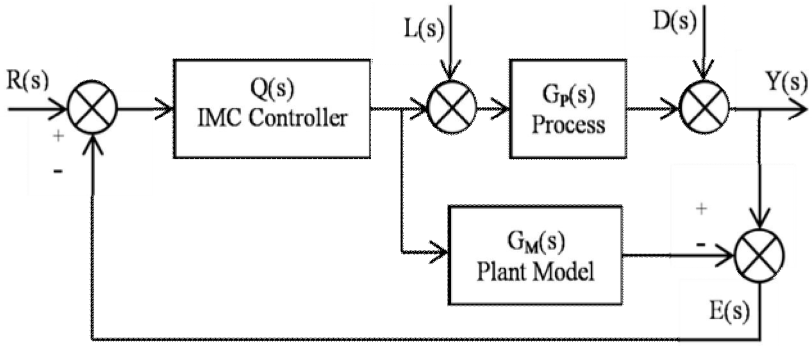


Figure 1. Basic IMC structure

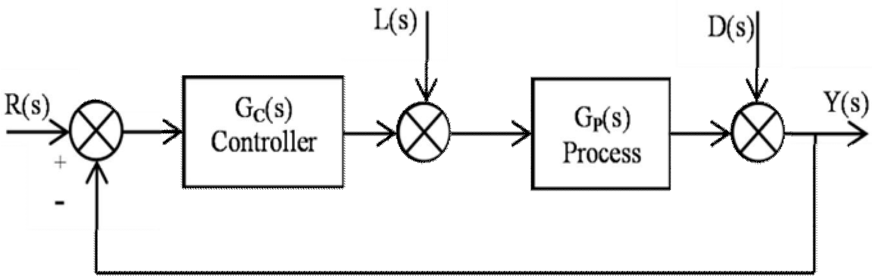


Figure 2. Feedback control structure

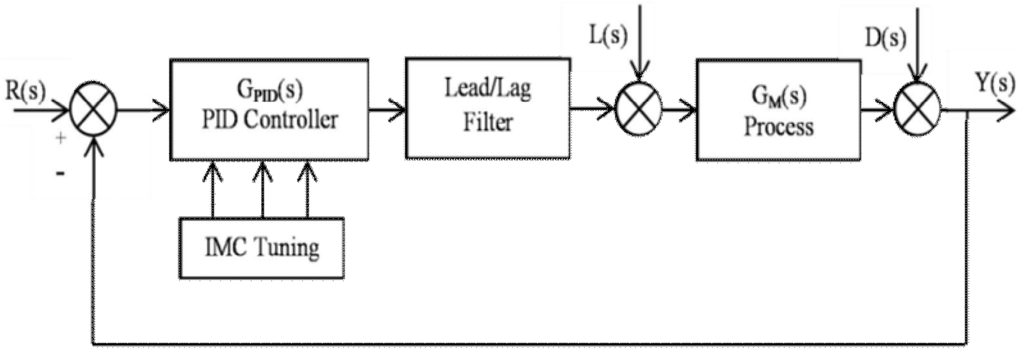


Figure 3. PID cascaded with filter

3. IMC-PID tuning rules for FOPTD model

The most widely used approximate or predictive model of the process more specifically chemical processes is the FOPTD given by (7). The procedure for obtaining the FOPTD model is explained in [2]. The plant model $G_M(s)$ is factored into invertible and non-invertible portions using all pass factorization, as the approximation of delay term $e^{-\theta s}$ with first order Padé approximation introduces non-minimum phase functions.

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

First order Padé Approximation

$$G_M(s) = \frac{K}{\tau s + 1}\left(\frac{1 - \frac{\theta}{2}}{1 + \frac{\theta}{2}}\right) \tag{8}$$

All pass factorization

$$G_M^-(s) = \frac{K}{\tau s + 1}, G_M^+(s) = \left(\frac{1 - \frac{\theta}{2}}{1 + \frac{\theta}{2}}\right) \tag{9}$$

The conventional IMC filter structure (Rivera et al.) for step input is of the form (10).

$$G_f(s) = \frac{1}{(\lambda s + 1)^n} \tag{10}$$

The resulting IMC controller $Q(s)$ is

$$Q(s) = \frac{1 + \tau s}{K(\lambda s + 1)} \tag{11}$$

The ideal feedback controller, equivalent of IMC controller is

$$G_C(s) = \frac{1}{Ks}\left(\frac{\frac{\theta}{2}\tau s^2 + \left(\frac{\theta}{2}+\tau\right)s + 1}{\frac{\theta}{2}\lambda s + (\theta+\lambda)}\right) \tag{12}$$

Rearranging (12), and comparing with (5), we obtain

$$K_P = \frac{\left(\frac{\theta}{2}+\tau\right)}{K(\theta+\lambda)}, T_i = \left(\frac{\theta}{2}+\tau\right),\ T_d = \left(\frac{\frac{\theta}{2}\tau}{\frac{\theta}{2}+\tau}\right) \tag{13}$$

$$b = c = d = 0,\ a = \frac{\frac{\theta}{2}\lambda}{(\theta+\lambda)} \tag{14}$$

The output response $Y(s)$ for FOPDT model of (6) for load disturbance with $R(s) = 0$ and $D(s) = 0$ is (15)

$$\frac{Y(s)}{\mathrm{L}(s)} = \frac{K\left(\frac{\theta}{2}\lambda s^2 + (\theta+\lambda)s\right)\left(1-\frac{\theta}{2}s\right)}{(1+\tau s)(1+\lambda s)\left(1+\frac{\theta}{2}s\right)^2} \tag{15}$$

It is observed that a slow process pole $s = -1/\tau$ exists in the dynamic relation between controlled output $Y(s)$ and load disturbance $\mathrm{L}(s)$. The effect of this, the response of the controller to disturbances becomes sluggish. To overcome this alternate filter of the form (16) is suggested.

Alternate form of filter is

$$G_f(s) = \frac{(\alpha s+1)^n}{(\lambda s+1)^{n+1}} \tag{16}$$

where n = 0 to 2.

IMC controller $Q(s)$ is

$$Q(s) = \frac{(1+\tau s)}{K}\frac{(\alpha s+1)^n}{(\lambda s+1)^{n+1}} \tag{17}$$

The ideal feedback controller, equivalent of IMC controller is

$$G_C(s) = \frac{\left(\frac{\theta}{2}\tau s^2 + \left(\frac{\theta}{2}+\tau\right)s + 1\right)(\alpha s+1)^n}{K\left((\lambda s+1)^{n+1}\left(1+\frac{\theta}{2}s\right) - (\alpha s+1)^n\left(1-\frac{\theta}{2}s\right)\right)} \tag{18}$$

The optimum filter for FOPTD systems is obtained with $n=2$

$$G_f(s)=\frac{(\alpha s+1)^2}{(\lambda s+1)^3} \tag{19}$$

The ideal feedback controller, equivalent of IMC controller for FOPTD is

$$G_C(s)=\left\{\frac{(\alpha s+1)^2}{Ks(3\lambda+\theta-2\alpha)}\frac{\left(\frac{\theta}{2}\tau s^2+\left(\frac{\theta}{2}+\tau\right)s+1\right)}{\left[\frac{\frac{\theta}{2}\lambda^3}{(3\lambda+\theta-2\alpha)}s^3+\frac{\left(\lambda^3+\frac{3}{2}\theta\lambda^2+\frac{\theta}{2}\alpha^2\right)}{(3\lambda+\theta-2\alpha)}s^2+\frac{\left(3\lambda^2+\frac{3}{2}\theta\lambda+\theta\alpha-\alpha^2\right)}{(3\lambda+\theta-2\alpha)}s+1\right]}\right\} \tag{20}$$

$$G_{PID}(s)=K_P\left(1+\frac{1}{T_i s}+T_d s\right)\left(\frac{\hat{d}s^3+ds^2+cs+1}{\hat{b}s^3+bs^2+as+1}\right) \tag{21}$$

Equating (20) and (21), we obtain

$$K_P=\frac{\frac{\theta}{2}+\tau}{K(3\lambda+\theta-2\alpha)},\ T_i=\left(\tau+\tfrac{\theta}{2}\right),\ T_d=\left(\frac{\frac{\theta}{2}\tau}{\frac{\theta}{2}+\tau}\right) \tag{22}$$

$$\hat{d}=0,\ d=2\alpha,\ \hat{b}=\alpha^2,\ a=\frac{\left(3\lambda^2+\frac{3}{2}\theta\lambda+\theta\alpha-\alpha^2\right)}{(3\lambda+\theta-2\alpha)},$$

$$b=\frac{\left(\lambda^3+\frac{3}{2}\theta\lambda^2+\frac{\theta}{2}\alpha^2\right)}{(3\lambda+\theta-2\alpha)},\ c=\frac{\frac{\theta}{2}\lambda^3}{(3\lambda+\theta-2\alpha)} \tag{23}$$

The slow process pole $s=-1/\tau$ is cancelled by the extra degree of freedom provided by α, it is obtained by computation of characteristic equation of the controller $\left[1-G_M(s)Q(s)\right]_{s=-\frac{1}{\tau}}=0$

$$\alpha=\tau\left[1-\sqrt{\left(1-\tfrac{\lambda}{\tau}\right)^3 e^{-\theta/\tau}}\right] \tag{24}$$

Assumptions are made so that α will not introduce undesired zeros in RHP, for this $\alpha>0$, implies $\tau>\lambda$.

4. Performance assessment

It is well-known that a well-designed control system should meet the following requirements besides nominal stability, it should possess Disturbance attenuation, Set point tracking and, Robust stability and/or robust performance. The first two requirements are traditionally referred to as ‘Performance’ and the third, ‘Robustness’ of a control system [9, 21].

4.1. Performance

The integral error is a good measure for evaluating the set point and disturbance response. The following are some commonly used criteria based on the integral error for a step set point or disturbance response.

$$IAE = \int_0^\infty |e(t)|\, dt \tag{25}$$

$$ISE = \int_0^\infty e(t)^2\, dt \tag{26}$$

$$ITAE = \int_0^\infty t\,|e(t)|\, dt \tag{27}$$

IAE penalizes small errors, ISE large errors and ITAE the errors that persist for a long time.

4.2. Robustness analysis

Robustness is the ability of the closed loop system to be insensitive to component variations. It is one of the most useful properties of feedback. Robustness is also what makes it possible to design feedback system based on strongly simplified models. It necessary to have quantitative ways to express how well a feedback system performs. Measures of performance and robustness are closely related. In closed loop system, the robustness performance is computed by the sensitivity function(S) which relates to disturbance rejection properties while the complementary sensitivity function (T) provides a measure of set point tracking performances.

$$S = \frac{1}{1 + G_C G_P} \tag{28}$$

$$T = \frac{G_C G_P}{1 + G_C G_P} \tag{29}$$

$|S(j\omega)|$ and $|T(j\omega)|$ are the amplitude ratios of S and T respectively. The maximum values of amplitude ratios provide useful measure of robustness and also serve as control system design criteria. The maximum sensitivity $M_S = \max_{\omega}|S(j\omega)$ is the inverse of the shortest distance from Nyquist plot to the critical point. As M_S decreases the robustness of closed loop system increases [23]. The second robustness measure is $M_T = \max_{\omega}|T(j\omega)$, referred as resonant peak. For a satisfactory control system M_S should be in the range of 1.2-2.0 and M_T should be in the range of 1.0-1.5 [9].

5. Simulation results

Four processes are considered for simulation to demonstrate effectiveness of the PID controller cascaded with lead/lag filter designed with proposed IMC filter for disturbance rejection. The processes considered have been studied and presented by other researchers and have different θ/τ ratio. The closed loop performance is evaluated using integral criteria Viz. IAE, ISE, ITAE and the robustness is evaluated with the maximum sensitivity M_S for each process for unit step load disturbance input. The IMC-PID tuning parameters are calculated to have same robustness in terms of maximum sensitivity M_S to ensure uniform comparison by varying λ which changes K_P only and does not have any variations in T_i, T_d. The performances of the IMC-PID tuning rules for the PID controller cascaded with conventional filter suggested by Rivera et al. [7] and filter proposed by Horn et al. [8], Liu and Gao [13], and the improved filter structure are compared for conciseness.

Example 1.

The lag time dominant FOPTD model $G(s)=\dfrac{100e^{-1s}}{100s+1}$ [12], with $\theta/\tau=0.01$ is used for study. Unit Step change in load disturbance input is applied at $t=0$. All the IMC-PID tuning techniques with different IMC filter structures were designed to have same robustness of $M_S=1.59$ by adjusting single tuning parameter λ .The simulation results of Figure 4 (a) and the Table 1 show that the PID controller obtained with improved IMC filter structure provides better disturbance rejection in comparison with conventional filter (Rivera et al.) and the filter proposed by Horn et al., and Liu and Gao. The robustness evaluation of the controllers is performed for model mismatch by incorporating perturbation of 20% in the three parameters of FOPTD model simultaneously, which has the form $G(s)=\dfrac{120e^{-0.8s}}{80s+1}$. The simulation results of Figure 4 (b) and Table 2 dictate the robustness of the PID controller tuned with proposed IMC filter structure.

Table 1. Performance of PID controller for example 1

Tuning Method	λ	K_P	T_i	T_d	M_s	Peak	IAE	ISE	ITAE
Proposed	3.155	8.081	100.5	0.498	1.59	1.607	10.93	12.74	64.25
Horn et al.	2.62	8.035	100.5	0.498	1.59	1.751	12.46	14.62	80.54
Rivera et al.	0.874	0.536	100.5	0.498	1.59	1.779	38.25	62.6	502

Table 2. Robustness analysis of PID controller for example1

Tuning Method	λ	K_P	T_i	T_d	M_s	Peak	IAE	ISE	ITAE
Proposed	3.155	8.081	100.5	0.498	1.59	1.622	10.64	12.04	59.1
Horn et al.	2.62	8.035	100.5	0.498	1.59	1.898	12.38	13.99	78.27
Rivera et al.	0.874	0.536	100.5	0.498	1.59	1.821	39.06	64.25	500.2

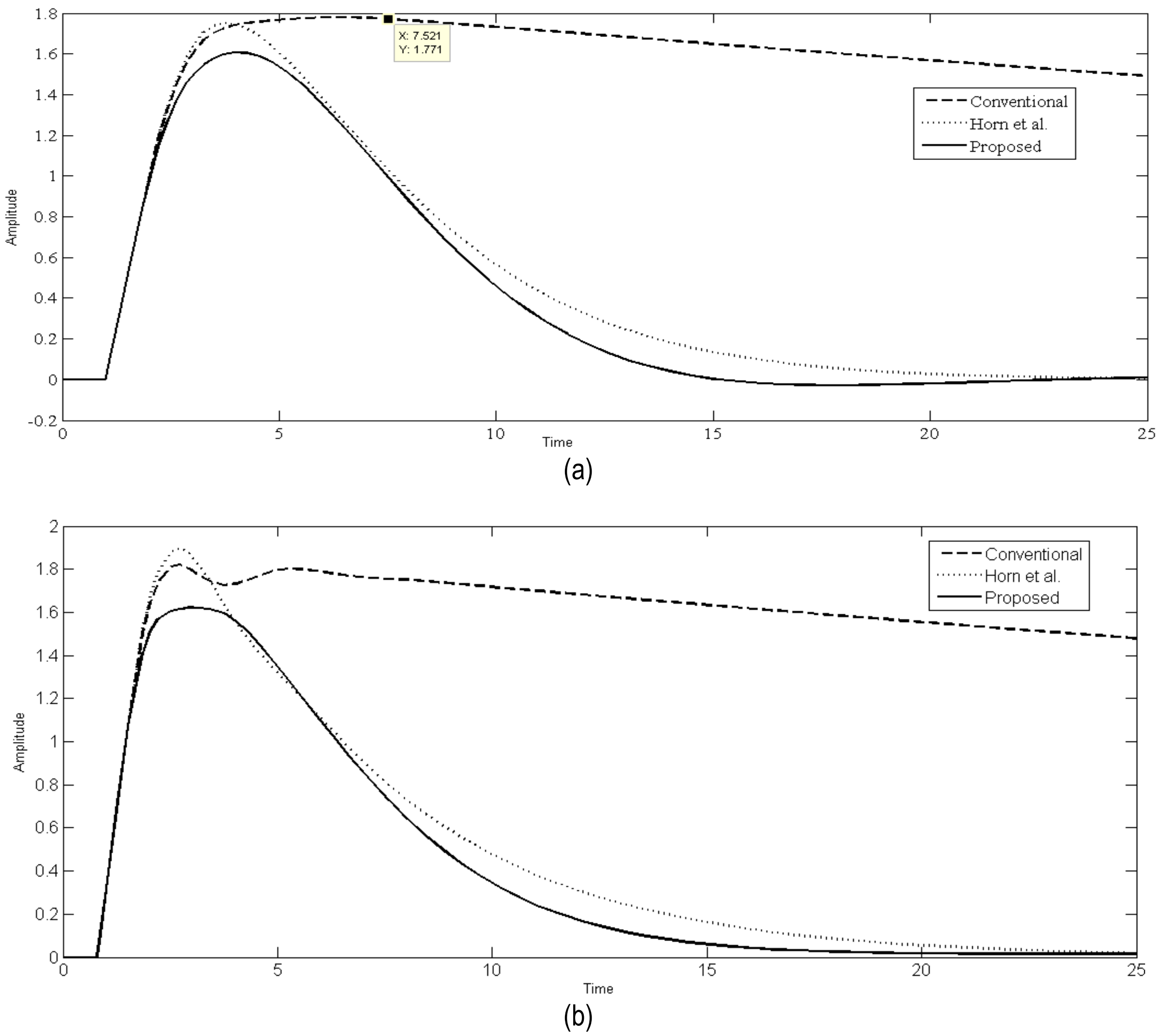


Figure 4. Responses for step load disturbance input for (a) nominal model; (b) 20% perturbed model

Example 2.

The FOPTD model $G(s)=\dfrac{1e^{-10s}}{100s+1}$ [8, 10], with $\theta/\tau=0.1$ is used for study. The robustness of $M_S=1.5$ is used for calculating the controller parameters. The result for unit step load disturbance is shown in Figure 5 (a) and the Table 3. The robustness evaluation of the controllers is performed for model mismatch by incorporating perturbation of 20% in the three parameters of FOPTD model simultaneously which has the form $G(s)=\dfrac{1.2e^{-8s}}{80s+1}$. The simulation results of Figure 5 (b) and Table 4 indicate the robustness of the proposed system in comparison with other methods considered.

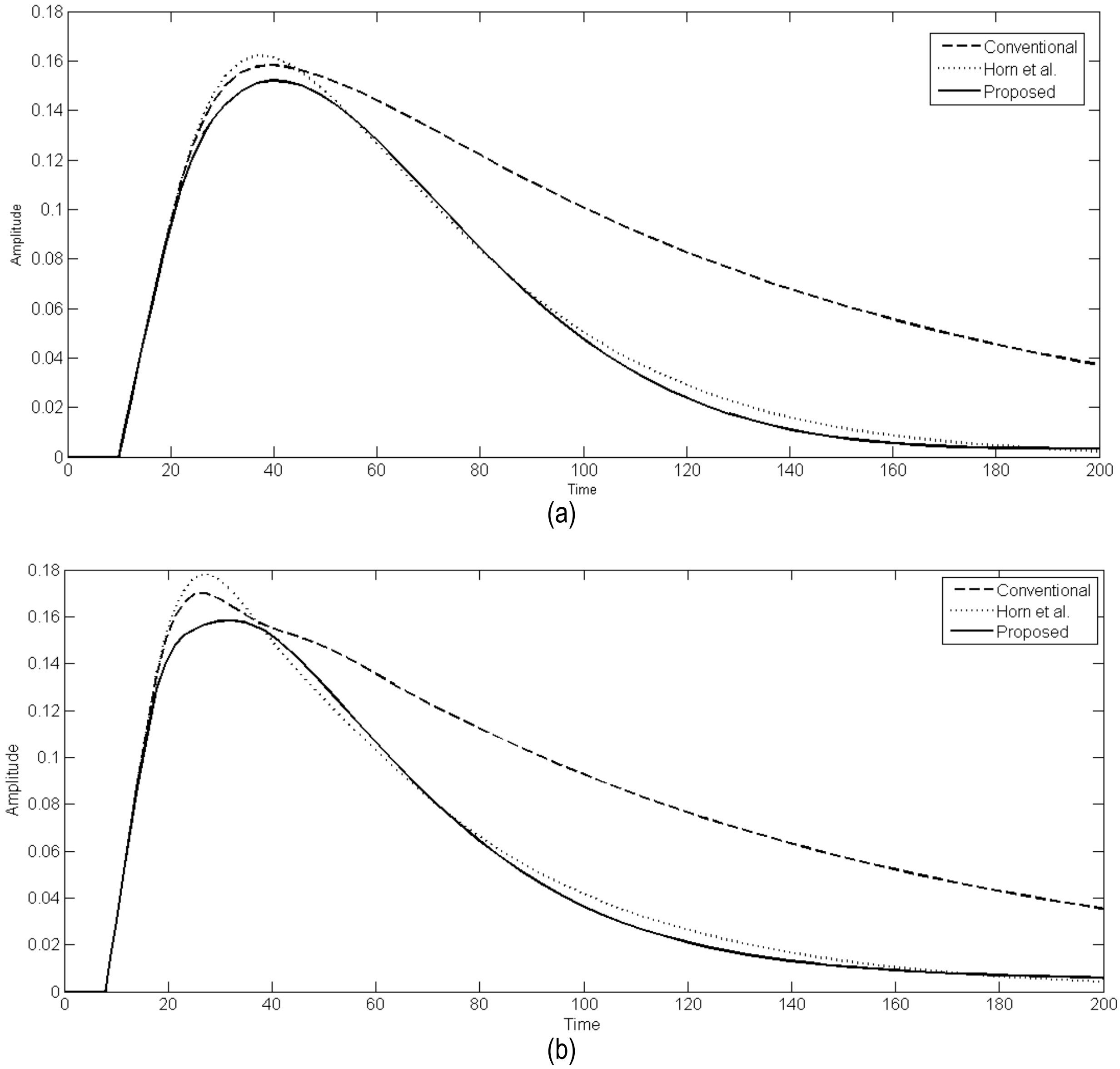


Figure 5. Responses for step load disturbance input for (a) nominal model; (b) 20% perturbed model

Table 3. Performance of PID controller for example 2

Tuning Method	λ	K_P	T_i	T_D	M_s	Peak	IAE	ISE	ITAE
Proposed	30	9.195	105	4.762	1.5	0.152	10.82	1.162	665.8
Horn et al.	25.8	9.201	105	4.762	1.5	0.162	11.34	1.239	714.5
Rivera et al.	11.35	4.918	105	4.762	1.5	0.158	17.63	1.947	1538

Table 4. Robustness analysis of PID controller for example 2

Tuning Method	λ	K_P	T_i	T_D	M_s	Peak	IAE	ISE	ITAE
Proposed	30	9.195	105	4.762	1.5	0.1583	10.75	1.146	628.5
Horn et al.	25.8	9.201	105	4.762	1.5	0.1785	11.23	1.23	665.3
Rivera et al.	11.35	4.918	105	4.762	1.5	0.1701	17.67	1.972	1461

Example 3.

The FOPTD model $G(s)=\frac{1e^{-1s}}{1s+1}$ [22], with $\theta/\tau=1$ is used for study. The robustness of $M_S=1.67$ is used for calculating the controller parameters. The result for unit step load disturbance of nominal model and 20% perturbed model $G(s)=\frac{1.2e^{-0.8s}}{1.2s+1}$ are shown in Figure 6 (a), Figure 6 (b), Table 5 and Table 6. The results indicate the reduction in peak in proposed system in comparison with other methods considered and it is observed, the settling time is increased because of increase in θ/τ ratio which produces a tail in the response, which intern has resulted in increase in IAE, ISE & ITAE.

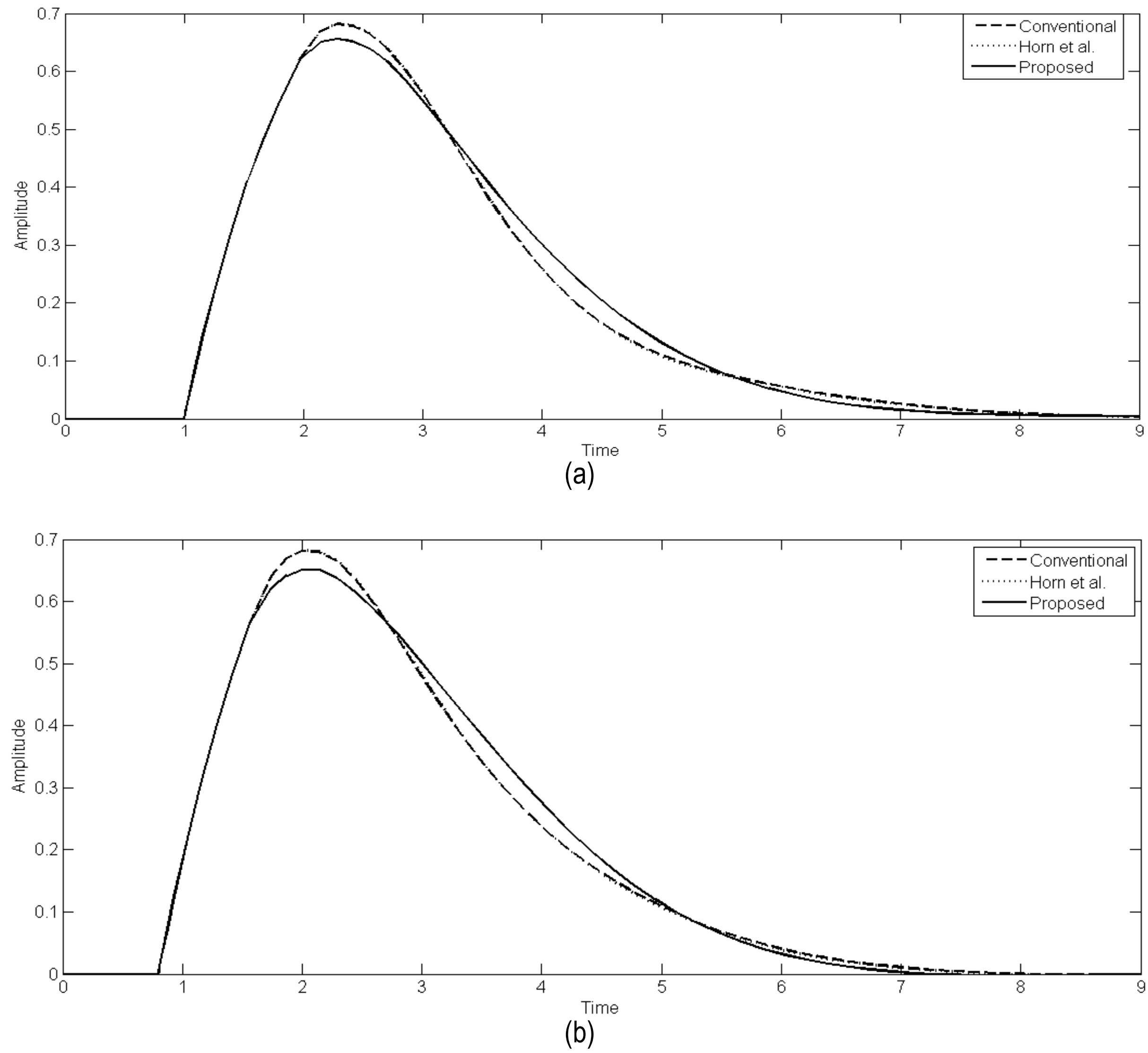


Figure 6. Responses for step load disturbance input for (a) nominal model; (b) 20% perturbed model

Table 5. Performance of PID controller for example 3

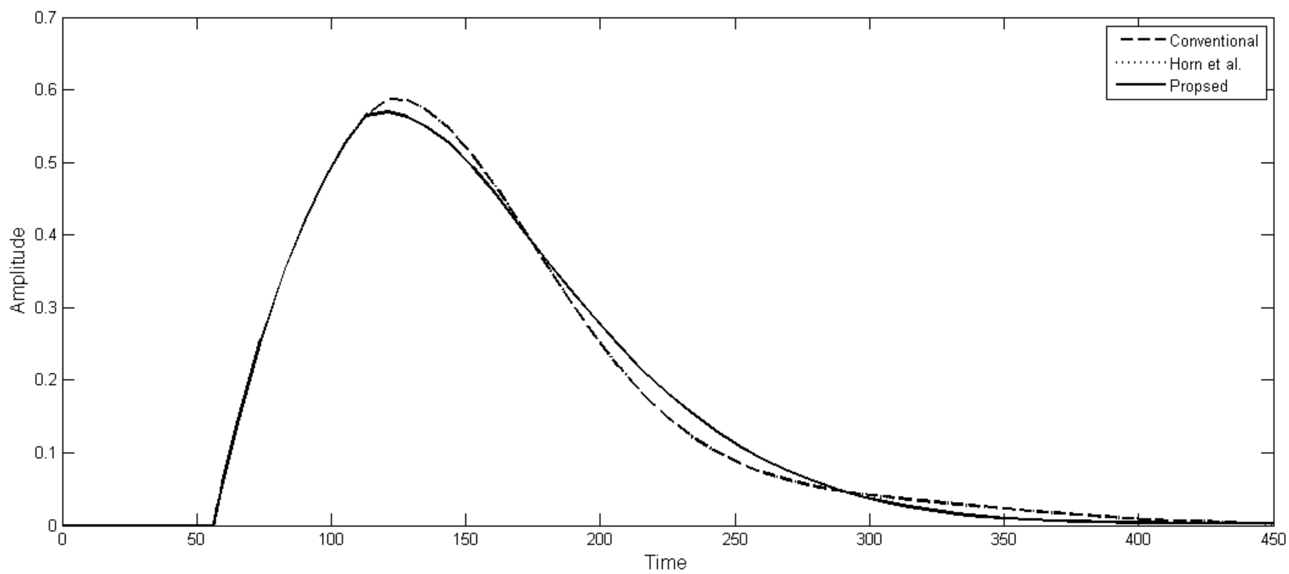
Tuning Method	λ	K_P	T_i	T_D	M_s	Peak	IAE	ISE	ITAE
Proposed	0.91	0.851	1.5	0.333	1.67	0.6562	1.748	0.7971	5.28
Horn et al.	0.86	0.869	1.5	0.333	1.67	0.6824	1.724	0.7971	5.18
Rivera et al.	0.731	0.867	1.5	0.333	1.67	0.6823	1.727	0.7954	5.21

Table 6. Robustness analysis of PID controller for example 3

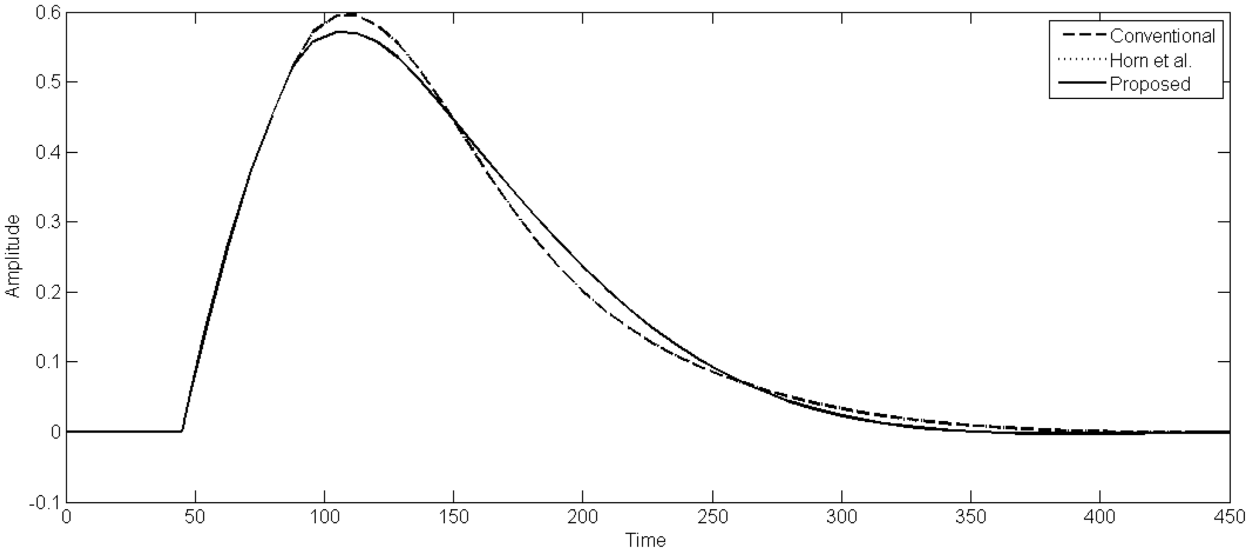
Tuning Method	λ	K_P	T_i	T_D	M_s	Peak	IAE	ISE	ITAE
Proposed	0.91	0.851	1.5	0.333	1.67	0.6513	1.763	0.8169	4.908
Horn et al.	0.86	0.869	1.5	0.333	1.67	0.6818	1.735	0.8099	4.79
Rivera et al.	0.731	0.867	1.5	0.333	1.67	0.6818	1.738	0.8082	4.815

Example 4.

The FOPTD model $G(s)=\dfrac{0.7717e^{-56.278s}}{42.934s+1}$ [2], with $\theta/\tau>1$ is used for study. The robustness of $M_S=1.69$ is used for calculating the controller parameters. The result for unit step load disturbance of nominal model and 20% perturbed model $G(s)=\dfrac{0.926e^{-45.022s}}{51.521s+1}$ are shown in Figure 7 (a), Figure 7 (b), Table 7 and Table 8. The results indicate the reduction in peak in proposed system in comparison with other methods considered and it is observed, the settling time is slightly increased because of increase in θ/τ ratio, which intern has resulted in increase in IAE, ISE & ITAE.



(a)



(b)

Figure 7. Responses for step load disturbance input for (a) nominal model; (b) 20% perturbed model

Table 7. Performance of PID controller for example 4

Tuning Method	λ	K_P	T_i	T_D	M_s	Peak	IAE	ISE	ITAE
Proposed	41.7	0.9621	71.073	16.998	1.69	0.5692	73.42	29.23	11309
Horn et al.	40.8	0.9698	71.073	16.998	1.69	0.5874	73.16	29.47	11314
Rivera et al.	38.7	0.9697	71.073	16.998	1.69	0.5874	73.17	29.46	11318

Table 8. Robustness analysis of PID controller for example 4

Tuning Method	λ	K_P	T_i	T_D	M_s	Peak	IAE	ISE	ITAE
Proposed	41.7	0.9621	71.073	16.998	1.69	0.5712	73.99	30	10425
Horn et al.	40.8	0.9698	71.073	16.998	1.69	0.5955	73.42	30.09	10316
Rivera et al.	38.7	0.9697	71.073	16.998	1.69	0.5955	73.43	30.08	10320

6. Conclusions

A design method for PID controller cascaded with lead/lag filter obtained using IMC technique using improved IMC filter structure was suggested for disturbance rejection. The suggested method provides good performance for disturbance rejection for lag dominant FOPTD processes. Four processes were considered for simulation study which have different θ/τ ratio. The simulations were conducted by tuning the PID controller to have same robustness in the form of M_S for uniform comparison. The robustness test for model mismatch was conducted by incorporating ±20% variation in the FOPTD model parameters simultaneously. The suggested method has proved to provide good disturbance rejection for processes with $\theta/\tau < 1$ compared to other methods. It is observed that if $\theta/\tau = 1$ or $\theta/\tau > 1$, the settling time is slightly increased and the overshoot is reduced in the proposed method. It is also suggested that for processes with $\theta/\tau = 1$ or $\theta/\tau > 1$ the single tuning parameter should be $0.8\tau < \lambda < \tau$. The suggested method provides good closed loop performance which was evaluated using integral criteria Viz. IAE, ISE, ITAE. The suggested method provides satisfactory responses for both nominal and perturbed models. A clear compromise between closed-loop performance and robustness to model inaccuracies is achieved with only one tuning parameter λ, which changes K_P only and does not have any variations in T_i, T_d.

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