Results in Control and Optimization 5 (2021) 100070

Contents lists available at ScienceDirect

Results in Control and Optimization

journal homepage: www.elsevier.com/locate/rico

Development of tuning free SISO PID controllers for First Order Plus Time Delay (FOPTD) and First Order Lag Plus Integral Plus Time Delay model (FOLIPD) systems based on partial model matching and experimental verification

Raju Yerolla, Chandra Shekar Besta *

Department of Chemical Engineering, National Institute of Technology Calicut, Kerala, 673601, India

ARTICLE INFO

Keywords:
PID controller
Stable system
FOPTD model
FOLIPD model
Setpoint tracking

ABSTRACT

This work aims to introduce a tuning-free PID controller for stable FOPTD and FOLIPD systems. The objective was achieved using a partial model-matching strategy; matching the coefficients of corresponding powers of s of the closed loop response of the model to the desired closed loop transfer function. Closed-loop performance is evaluated by considering a unit step change in the process model and compared the results with other methods reported earlier in the literature. Input and output performances were evaluated using error analyses and total variation. The robustness of the proposed method was assessed via incorporation of uncertainties in the process model parameters. The proposed method was also experimentally validated for FOPTD model using a temperature controlled lab. It was concluded that the method was analytically derived and model based with a key advantage that the resultant PID required no tuning parameter.

1. Introduction

The PID (Proportional Integral Derivative) controller is employed mainly in process industry applications to provide robust performance for stable, unstable, and nonlinear processes. PID controllers are ubiquitous in the process control industry because of their limited number of tuning parameters and ease of implementation than advanced control [1]. More than half of the controller strategies are still using PID control, yet finding optimal values is not easy without an effective method [2]. Mostly dynamic processes are defined in terms of the FOPTD (First Order plus Time Delay) model for designing the PID controller.

Although many control theory developments, the PID controller is widely used in the process control industry [3]. For more than two decades, industries have attracted IMC (Internal Model Control) based PID tuning methods due to improved performance and a single tuning parameter. IMC-PID tuning methods [3–8], and DS (Direct Synthesis) methods [9,10] are the two prominent examples of typical tuning methods to obtain the desired closed-loop performance. The IMC-based PID controller provides a better setpoint response but a sluggish response to disturbances, especially in small time delay to time constant ratio processes.

In the literature, traditional PID control tuning methods include trial and error method, Ziegler–Nichols step response method, Ziegler–Nichols frequency response method [11], Relay Tuning method [12], and Cohen–Coon method [13]. The computational approach, often used for data modeling and cost-function optimization has been used for PID tuning. Practical implementation strategies require optimization of the cost function.

Following the emergence of traditional PID, better performance of complex systems controller design requires new tuning control strategies. Besharati Rad proposed a new system of auto-tuning [14]. This tuning method is fast and is used for tuning PID controllers

* Corresponding author.
E-mail address: schandra@nitc.ac.in (C.S. Besta).

https://doi.org/10.1016/j.rico.2021.100070
Received 4 May 2021; Received in revised form 25 August 2021; Accepted 5 November 2021
Available online 10 November 2021

that do not have an automatic feature. Koivo and Tanttu conducted a survey on the PID controller of SISO (Single Input Single Output) for various configuration modes and MIMO (Multiple Input Multiple Output) [15]. Researchers have contributed to the development of tuning techniques such as auto-tuning [16], model matching method [17], and genetic algorithm method [18]. The assumptions made by the above methods are invested in a well-known transfer function, and PID parameters are attained by solving a set of linear equations. L Aguirre developed an algorithm for control design based on pade approximation, matching coefficients, and Markov parameters [18]. Jones proposes genetic algorithm techniques as an alternative to digital PID controllers [18]. This genetic algorithm is attractive, even in digital algorithms, as the same basic method can still be easily applied to PID controllers with complex flexible plants with highly interactive dynamics. Alberto Lava suggested a relay-based algorithm for automatic PID tuning by defining a single point of a process frequency response [19]. When the process considered is closed to reality, the algorithm inclines to provide satisfactory performance and accuracy. Astrom analyzed various adaptive strategies such as scheduling gains and automated tuning [12]. This tuning strategy depends on a maximum peak resonance specification that prompts simple tuning parameter expressions. PID tuning rules such as time domain-based design and fuzzy logic tuning were proposed by Antonio and Visioli [20], respectively. Comino noted that PID controllers are poorly tuned, and efforts have been made to deal with the problem systematically [21]. In his contribution that incorporates PID tuning strategies commonly utilized and to explored a few recent effective strategies. Robust and optimum PI and PID controller tuning have been suggested [21]. Lennartson presented an analytical design strategy and a RIMC (Robust Internal Model Control) evaluation procedure. The IMC tuning parameter change is substituted by specific tuning parameters relevant to crucial medium frequency and higher frequency robustness characteristics [22].

The proposed method focuses on designing the PID controller design for the FOPTD and FOLIPD (First Order Lag Integrating plus Time Delayed model) models and provides the advantage of tuning free PID controller design while being analytically derived and model-based. The closed-loop control performance was evaluated using error analysis, total variation, and robustness by introducing the uncertainty in the process model parameters.

2. Proposed method

Let us consider the generalized transfer function of $G_p(s)$ of the process:

$$G_p(s) = \frac{1}{g_0 + g_1 s + g_2 s^2 + g_3 s^3 + \cdots} \tag{1}$$

Considered the PID controller transfer function, $G_C(s)$ and given by:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{2}$$

Where $K_P = K_c$, $K_i = \frac{K_c}{\tau_i}$ and $K_d = K_c \tau_d$ are PID controller settings called propositional gain, integral gain, and derivative gain.

The closed-loop transfer function of the process, $G_p(s)$ and controller $G_c(s)$ is given by

$$G_{cl}(S) = \frac{G_c(s)\, G_p(s)}{1 + G_c(s)\, G_p(s)} \tag{3}$$

The transfer function, $G_r(s,\sigma)$ of the reference model is given by:

$$G_r(s,\sigma) = \frac{1}{1 + s\sigma + \alpha_2 (s\sigma)^2 + \alpha_3 (s\sigma)^3 + \alpha_4 (s\sigma)^4 + \cdots} \tag{4}$$

Where α_2, α_3, α_4 are weighting factor, and σ is series coefficient in general reference model, and by equating Eq. (3) and Eq. (4) then the controller $G_c(s)$ is given by:

$$G_c(s) = \frac{G_r(s,\sigma)}{G_p(s)(1 - G_r(s,\sigma))} \tag{5}$$

$$G_c(s) = \frac{g_0 + g_1 s + g_2 s^2 + g_3 s^3}{s\sigma(1 + \alpha_2 (s\sigma) + \alpha_3 (s\sigma)^2 + \alpha_4 (s\sigma)^3)} \tag{6}$$

Expanding the controller equation (6), by Maclaurin's series

$$\begin{aligned} G_c(s) \quad = \quad & \tfrac{g_0}{s\sigma} + \tfrac{g_1}{\sigma} - \alpha_2 g_0 - s\left(\alpha_2 g_1 - \tfrac{g_2}{\sigma} + \tfrac{g_0\left(\sigma^2\alpha_3 - \sigma^2\alpha_2^2\right)}{\sigma}\right) \\ & -s^2\left(\alpha_2 g_2 - \tfrac{g_3}{\sigma} + \tfrac{g_1\left(\alpha_3\sigma^2 - \alpha_2^2\sigma^2\right)}{\sigma} - \tfrac{g_0\left(\alpha_2\sigma\left(\alpha_3\sigma^2 - \alpha_2^2\sigma^2\right) - \alpha_4\sigma^3 + \alpha_2\alpha_3\sigma^3\right)}{\sigma}\right) + \cdots \end{aligned} \tag{7}$$

Equating the parallel PID transfer function in Eq. (2) with Eq. (7) can get PID controller settings for the generalized reference model.

$$K_p = \frac{g_1}{\sigma} - \alpha_2 g_0 \tag{8}$$

$$K_i = \frac{g_0}{\sigma} \tag{9}$$

$$K_d = -[\alpha_2 g_1 - \frac{g_2}{\sigma} + \frac{g_0\left(\sigma^2\alpha_3 - \sigma^2\alpha_2^2\right)}{\sigma}] \tag{10}$$

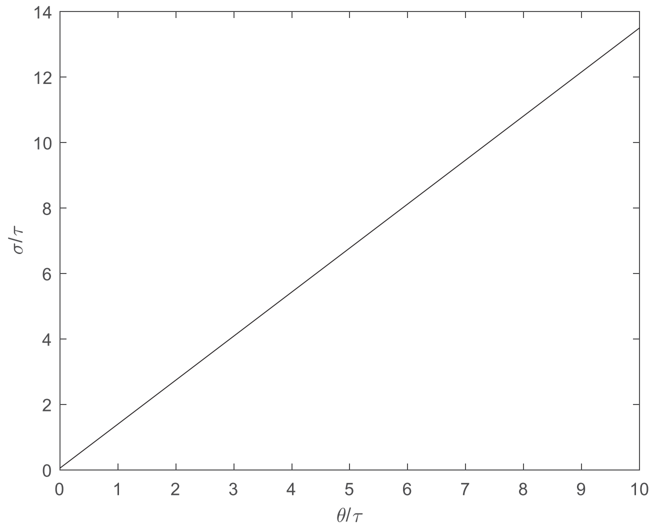


Fig. 1. By varying θ/τ from 0 to 10 corresponding values of σ/τ for FOPTD stable system.

$$0 = -\alpha_2 g_2 + \frac{g_3}{\sigma} - \frac{g_1\left(\alpha_3\sigma^2 - \alpha_2^2\sigma^2\right)}{\sigma} + \frac{g_0\left(\alpha_2\sigma\left(\alpha_3\sigma^2 - \alpha_2^2\sigma^2\right) - \alpha_4\sigma^3 + \alpha_2\alpha_3\sigma^3\right)}{\sigma} \tag{11}$$

2.1. The proposed method for FOPTD stable model

Consider the FOPTD stable process model

$$G_p(s) = \frac{Ke^{-\theta s}}{(1+\tau s)} \tag{12}$$

The process model in Eq. (12) is expanded and reduced by using Maclaurin's series, and the process model is given by

$$G_p(s) = \frac{1}{\frac{1}{K} + \frac{\theta+\tau}{K}s + \frac{0.5\theta^2+\theta\tau}{K}s^2 + \frac{0.166\theta^3+0.5\theta^2\tau}{K}s^3 + \cdots} \tag{13}$$

The following relations will be obtained using the partial model matching method to the process model in Eq. (13) to the controller Eqs. (8)–(10).

$$K_p = \frac{\theta+\tau}{K\sigma} - \frac{\alpha_2}{K} \tag{14}$$

$$K_i = \frac{1}{K\sigma} \tag{15}$$

$$K_d = \frac{-\alpha_2\sigma(\theta+\tau) + 0.5\theta^2 + \tau\theta - \alpha_3\sigma^2 + \alpha_2^2\sigma^2}{K\sigma} \tag{16}$$

$$0 = \sigma^3\left(2\alpha_2\alpha_3 - \alpha_2^3\right) + \sigma^2\left(\alpha_2^2 - \alpha_3^2\right)(\tau+\theta) - \sigma\left(0.5\theta^2 + \tau\theta\right)\alpha_2 + 0.1667\theta^3 + 0.5\tau\theta^2 \tag{17}$$

By using Eq. (17), the value of σ can be calculated by taking α ($\alpha_1 = 1, \alpha_2 = 0.5, \alpha_3 = 0.15, \alpha_4 = 0.03$) values from the reference model [1] by varying θ/τ from 0 to 10. Corresponding values of σ/τ are plotted in Fig. 1.

From Fig. 1, the value of $\sigma = 1.34520\theta + 0.0504\tau$ is obtained, this value contributes to a reduction of overshoot, and substituting these values in Eqs. (14)–(16) will get the PID controller settings for FOPTD stable model.

$$K_p = \frac{0.3274\theta + 0.9748\tau}{k(1.34520\theta + 0.0504\tau)} \tag{18}$$

$$K_i = \frac{1}{k(1.34520\theta + 0.0504\tau)} \tag{19}$$

$$K_d = \frac{0.00835\theta^2 - 0.0249\tau^2 + 0.31635\theta\tau}{k(1.34520\theta + 0.0504\tau)} \tag{20}$$

Where $K_p, K_i,$ andK_d are the PID controller setting for FOPTD stable model called proportional gain, integral gain, and derivative gain, respectively. The limitation of the proposed method, ratio of a time delay to a time constant is up to 2.5.

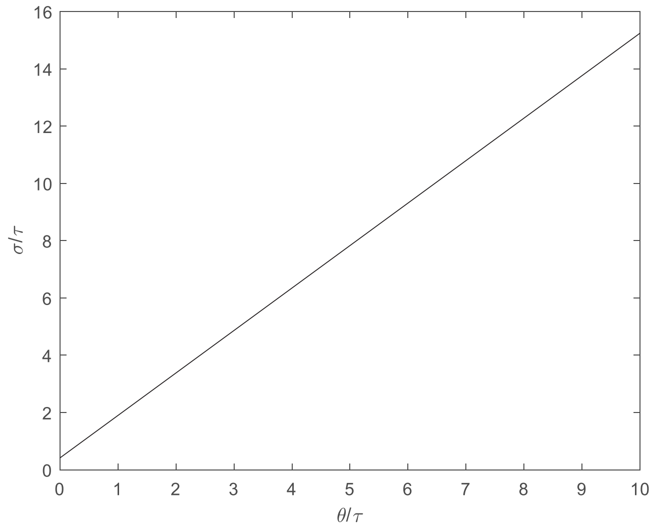


Fig. 2. By varying θ/τ from 0 to 10 corresponding values of σ/τ for FOLIPD stable system.

2.2. The proposed method for the FOLIPD model

Consider the FOLIPD stable process model

$$G_p(s) = \frac{Ke^{-\theta s}}{s(1+\tau s)} \tag{21}$$

The process model in Eq. (21) is expanded and reduced by using Maclaurin's series, and the process model is given by

$$G_p(s) = \frac{1}{\frac{1}{K}s + \frac{\theta+\tau}{K}s^2 + \frac{0.5\theta^2+\theta\tau}{K}s^3 + \frac{0.1667\theta^3+0.5\theta^2\tau}{K}s^4 + \cdots} \tag{22}$$

The following relations will be obtained using the partial model matching method to the process model Equation (22) to the controller Eqs. (8)–(10).

$$K_p = \frac{1}{K\sigma} \tag{23}$$

$$K_i = 0 \tag{24}$$

$$K_d = \frac{-\alpha_2\sigma + \tau + \theta}{K\sigma} \tag{25}$$

$$0 = \frac{-\alpha_2(\tau+\theta)}{K} + \frac{0.5\theta^2 + \theta\tau}{K\sigma} - \frac{\alpha_3\sigma^2}{K\sigma} + \frac{\alpha_2\sigma^2}{K\sigma} \tag{26}$$

By using Eq. (26), the value of σ will be calculated by taking α ($\alpha_1 = 1, \alpha_2 = 0.5, \alpha_3 = 0.15, \alpha_4 = 0.03$) values from the reference model [1] by varying θ/τ from 0 to 10, found the corresponding values of σ/τ are plotted as shown in Fig. 2.

From Fig. 2, the value of $\sigma = 1.4832\theta + 0.415\tau$ is obtained, this value contributes to a reduction of overshoot. Substituting this value throughout Eqs. (23)–(25) will provide the PID controller settings for FOLIPD stable model as follows.

$$K_p = \frac{1}{K(1.4832\theta + 0.415\tau)} \tag{27}$$

$$K_i = 0 \tag{28}$$

$$K_d = \frac{0.2854\theta + 0.7923\tau}{K(1.4832\theta + 0.415\tau)} \tag{29}$$

Where K_p, K_i and K_d are the PID controller setting and are called proportional gain, integral gain, and derivative gain.

3. Simulation results

Simulation studies are carried out using the MATLAB/Simulink 2019b package. The proposed method is focuses on dealing with set point tracking application. Considered a unit step change to evaluate the closed loop performance, the output performance evaluated by computing Integral Time Absolute Error, and the input performance is evaluated by computing Total Variation. The experimental validation of the proposed PID controller design is carried out using the TC (Temperature Control) lab device. The proposed controller settings are also working for load rejection (regulatory problem) by detuning controller settings.

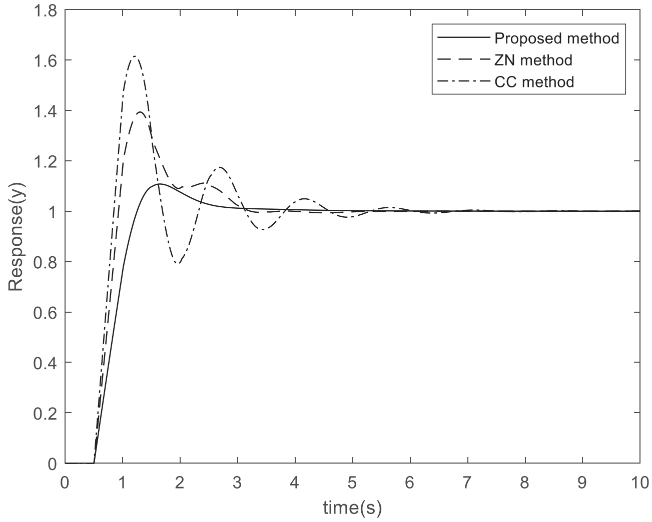


Fig. 3. Setpoint tracking response for a unit step change in example 1. ($k = 1, \tau = 1, \theta = 0.5$).

Table 1
ITAE, TV and overshoot values for FOPTD stable system example 1. ($k = 1, \tau = 1, \theta = 0.5$).

Setpoint tracking			
Method	ITAE	TV	Overshoot
CC method	1.395	2.916	6.3
ZN method	0.870	2.284	4.0
Proposed method	0.607	1.574	1.0

Table 2
Robust Analysis for FOPTD stable system example 1. ($k = 1, \tau = 1, \theta = 0.5$).

Method	Uncertainty in k_p - 20%			Uncertainty in τ - 20%			Uncertainty in θ- 20%		
	ITAE	TV	Overshoot	ITAE	TV	Overshoot	ITAE	TV	Overshoot
CC method	1.549	2.916	6.3	6.215	2.916	9.1	1.288	2.916	6.0
ZN method	0.867	2.284	4.2	1.390	2.284	6.5	0.891	2.284	3.8
Proposed method	0.607	1.574	1.1	0.935	1.574	2.4	0.634	1.574	1.0

3.1. Simulation results for the FOPTD model

3.1.1. Example 1

Consider FOPTD stable process model with $K = 1, \tau = 1, \theta = 0.5$ for the proposed method, the PID controller settings are $K_c = 1.5747, K_i = 1.3831, K_d = 0.1872$. The PID controller setting by Ziegler's Nicholas method [11] are $K_c = 2.2842, K_i = 2.6576, K_d = 0.4908$ and by Cohen Coon method [13] are $K_c = 2.9167, K_i = 2.8333, K_d = 0.4861$. For a unit set point change in the process, the closed loop performance is plotted in Fig. 3. The proposed method results have been compared with Ziegler's Nicholas method, and Cohen Coon method. The comparison results show that the proposed method gave smooth and better closed loop control performance in terms of settling time, and overshoot, and error analysis which is listed in Table 1. Computing ITAE and TV evaluate the input and output control performance, and these values are small for proposed method compared to other methods. The Robustness is assessed by performing the uncertainties in the process model parameters. However, the PID controller settings used were the same. Fig. 4 shows the 20% uncertainties in the process model parameters. The proposed method still shows better closed loop control performance. The corresponding errors, overshoot and total variation listed in the Table 2.

3.1.2. Example 2

Consider FOPTD stable process model with $K = 1, \tau = 5, \theta = 1$, for the proposed method, the PID controller settings are $K_c = 3.2566, K_i = 0.6261, K_d = 0.6058$. The PID controller setting by Ziegler's Nicholas method [11] are $K_c = 5.10, K_i = 2.7456, K_d = 2.3683$ and PID controller settings by Cohen Coon method [13] are $K_c = 6.9167, K_i = 3.0417, K_d = 2.4269$. For a unit setpoint change in the process, the closed loop performance is plotted in Fig. 5. The proposed method results have been compared with Ziegler's Nicholas method, and Cohen Coon method. The comparison results show the proposed method gave smooth and better closed loop control performance in terms of settling time, and overshoot, and error analysis which is listed in the Table 3. Computing ITAE and TV

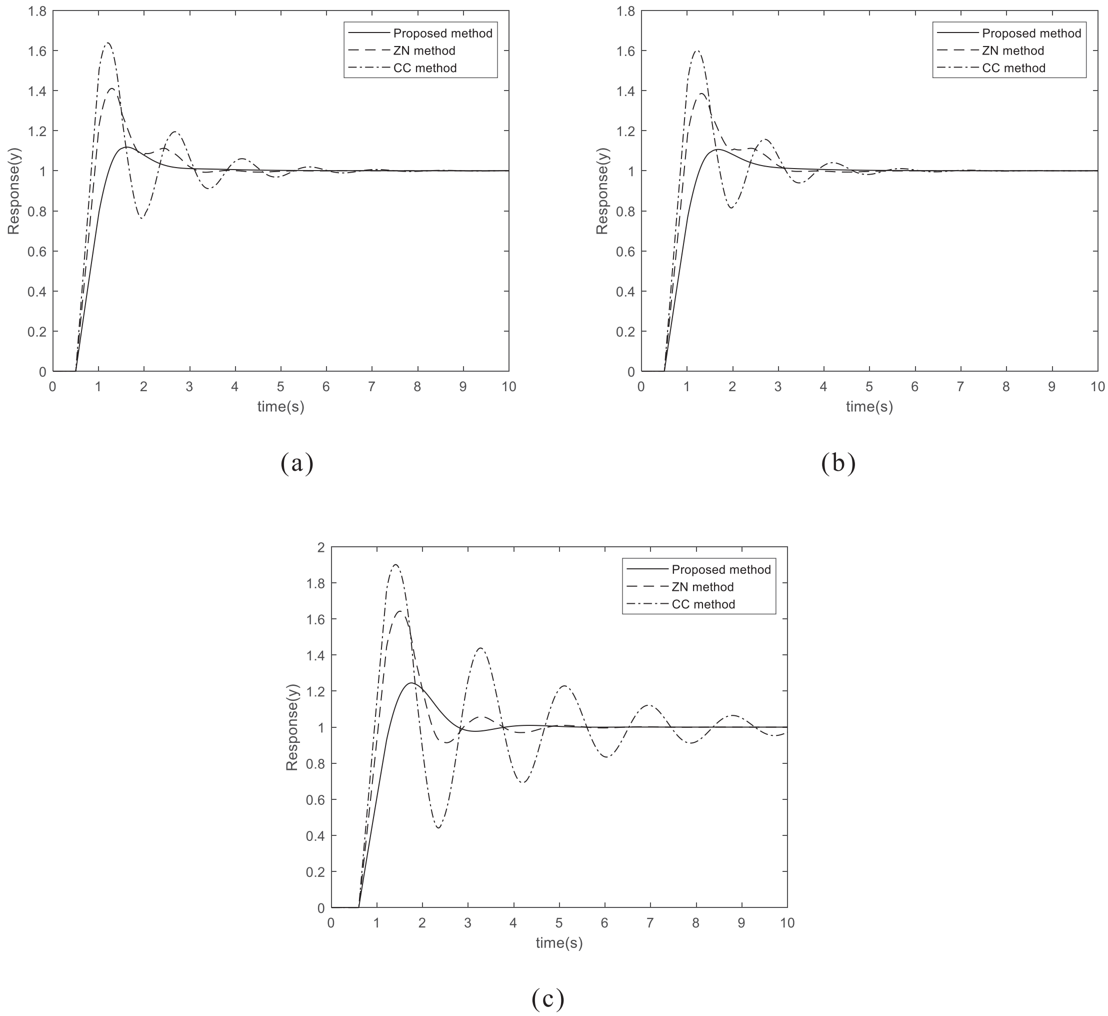


Fig. 4. Setpoint tracking under 20% parameter uncertainty, for example 1. ($k = 1, \tau = 1, \theta = 0.5$). (a) Uncertainty in K (b) Uncertainty in τ (c) Uncertainty in θ.

Table 3
ITAE, TV, and Overshoot values for FOPTD stable system example 2. ($k = 1, \tau = 5, \theta = 1$).

Setpoint tracking			
Method	ITAE	TV	Overshoot
CC method	6.634	3.256	8.4
ZN method	6.303	5.10	5.5
Proposed method	3.154	6.910	0.6

evaluate the input and output control performance, and these values are small for proposed method compared to other methods. Robustness is assessed by performing the uncertainties in the process model parameters. However, the PID controller settings used were the same. Fig. 6 shows the 20% uncertainties in the process model parameters. The proposed method still shows better closed loop control performance. The corresponding errors, overshoot and total variation listed in the Table 4.

3.2. Simulation results for the FOLIPD model

3.2.1. Example 3

Consider FOLIPD stable process model with $K = 1, \tau = 1, \theta = 4$, for the proposed method, the PID controller settings are $K_c = 0.1575, K_i = 0, K_d = 0.3046$. The PID controller setting by the Sree method[23] are $K_c = 0.2175, K_i = 0.0217, K_d = 0.690$ and by Hagglund method [24] were $K_c = 0.0938, K_i = 0.0019, K_d = 0.230$. For a unit set point change in the process, the closed loop performance is plotted in Fig. 7. The results of the proposed method have been compared with the Sree method and Hagglund

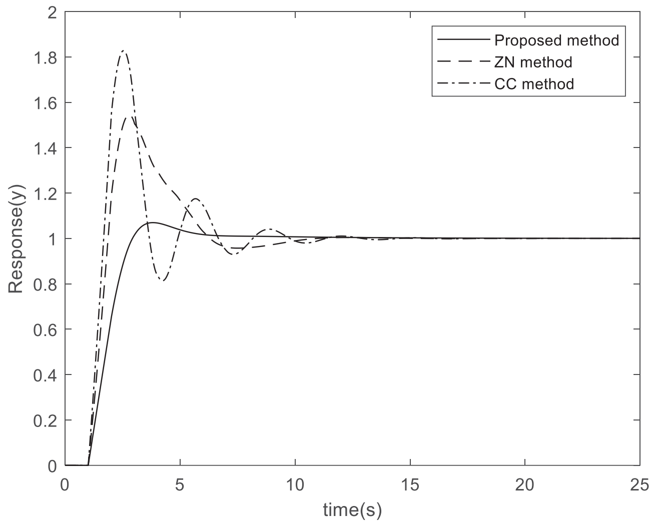


Fig. 5. Setpoint tracking response for a unit step change in example 2. ($k = 1, \tau = 5, \theta = 1$).

Table 4
Robust Analysis for FOPTD stable system example 2. ($k = 1, \tau = 5, \theta = 1$).

Method	Uncertainty in k_p - 20%			Uncertainty in τ - 20%			Uncertainty in θ- 20%		
	ITAE	TV	Overshoot	ITAE	TV	Overshoot	ITAE	TV	Overshoot
CC method	7.342	6.916	8.4	4.437	6.916	6.6	7.759	6.916	8.7
ZN method	6.157	5.10	5.5	8.70	5.10	4.8	6.427	5.10	5.7
Proposed method	3.140	3.256	0.8	5.539	3.256	0.5	3.325	3.256	8.1

Table 5
ITAE, TV, and Overshoot values for FOLIPD stable system example 3. ($k = 1, \tau = 1, \theta = 4$).

Setpoint tracking			
Method	ITAE	TV	Overshoot
Hagglund method	591.2	0.093	1.3
Sree method	241.5	0.217	5.9
Proposed method	39.59	0.159	0.2

Table 6
Robust Analysis for FOLIPD stable system example 3. ($k = 1, \tau = 1, \theta = 4$).

Method	Uncertainty in k_p - 20%			Uncertainty in τ - 20%			Uncertainty in θ- 20%		
	ITAE	TV	Overshoot	ITAE	TV	Overshoot	ITAE	TV	Overshoot
Hagglund method	492.4	0.093	1.3	594.2	0.093	1.3	62.59	0.093	1.4
Sree method	199.1	0.217	7.2	251	0.217	6.4	270.1	0.217	9.0
Proposed method	42.7	0.159	1.1	43.21	0.159	0.4	62.59	0.159	1.3

method. The comparison results show that the proposed method gave smooth and better closed loop control performance in terms of settling time, overshoot, and error analysis listed in Table 5. Computing ITAE and TV evaluate the input and output control performance, and these values are small for proposed method compared to other methods Robustness is assessed by performing the uncertainties in the process model parameters. However, the PID controller settings used were the same. Fig. 8 shows the 20% uncertainties in the process model parameters. The proposed method still shows better-closed loop control performance. The corresponding errors, overshoot, and total variation listed in Table 6.

3.2.2. Example 04

Consider FOLIPD stable process model with $K = 1.2, \tau = 1, \theta = 4.8$, for the proposed method, the PID controller settings are $K_c = 0.1106, K_i = 0, K_d = 0.2391$. The PID controller setting by the Sree method [23] are $K_c = 0.1518, K_i = 0.0126, K_d = 0.5417$ and PID controller setting by Hagglund method [24] are $K_c = 0.0650, K_i = 0.0011, K_d = 0.1819$. For a unit set point change in the process, the closed loop performance is plotted in Fig. 9. The proposed method results have been compared with the Sree method and Hagglund method. The comparison results show the proposed method gave smooth and better closed loop control performance in

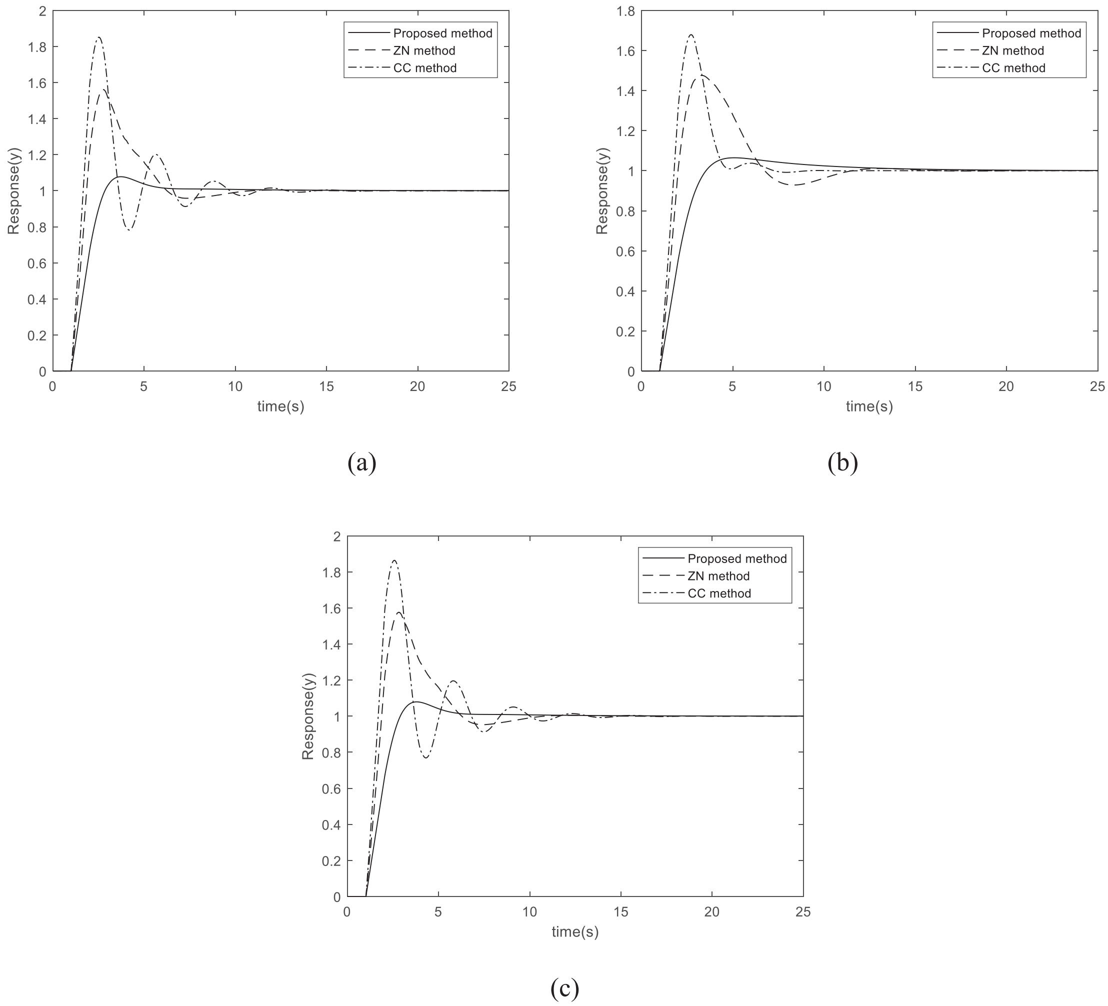


Fig. 6. Setpoint tracking under 20% parameter uncertainty, for example, 2. ($k = 1, \tau = 5, \theta = 1$). (a) Uncertainty in K (b) Uncertainty in τ (c) Uncertainty in θ.

Table 7
ITAE, TV, and Overshoot values for FOLIPD stable system example 4. ($k = 1.2, \tau = 1, \theta = 4.8$).

Setpoint tracking			
Method	ITAE	TV	Overshoot
Hagglund method	709.5	0.065	0.9
Sree method	322.6	0.151	5.8
Proposed method	54.2	0.11	0.2

terms of settling time, overshoot, and error analysis, listed in Table 7. Computing ITAE and TV evaluate the input and output control performance, and these values are small for proposed method compared to other methods. Robustness is assessed by performing the uncertainties in the process model parameters. However, the PID controller settings used were the same. Fig. 10 shows the 20% uncertainties in the process model parameters. The proposed method still shows better closed-loop control performance. The corresponding errors, overshoot, and total variation listed in Table 8.

4. Experimental validation of proposed PID controller for the FOPTD model

The validation of proposed controller is assessed by using a TC lab device [25] as show in Fig. 11. TC lab is a standard hardware benchmark for testing different controller settings and is a printed circuit board shield that connects to an Arduino microcontroller. The proposed method's evaluation has been carried over in six steps: dynamic step test, process model identification, model verification, controller design, and controller testing using different methods against the proposed method. Firstly, it conducted

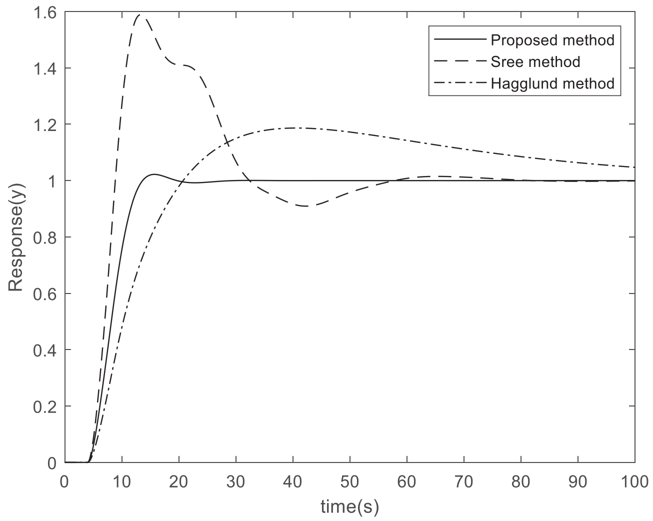


Fig. 7. Setpoint tracking response for a unit step change in example 3 ($k = 1, \tau = 1, \theta = 4$).

Table 8
Robust Analysis for FOLIPD stable system example 4. ($k = 1.2, \tau = 1, \theta = 4.8$).

Method	Uncertainty in k_p - 20%			Uncertainty in τ - 20%			Uncertainty in θ- 20%		
	ITAE	TV	Overshoot	ITAE	TV	Overshoot	ITAE	TV	Overshoot
Hagglund method	597.9	0.065	1.1	714.1	0.065	1.0	730.2	0.65	1.3
Sree method	259.2	0.151	7.2	332.9	0.151	6.3	360.6	0.151	9.1
Proposed method	58.55	0.11	1.0	58.54	0.11	0.4	86.87	0.11	1.1

Table 9
ITAE, TV, and Overshoot values for FOPTD identified process. ($k = 6.55, \tau = 140, \theta = 15$).

Setpoint tracking			
Method	ITAE	TV	Overshoot
CC method	1516	1.9381	9.1
ZN method	1819	1.4024	6.0
Proposed method	732.6	0.7926	0.4

Table 10
Robust Analysis for FOPTD IDENTIFIED process. ($k = 6.55, \tau = 140, \theta = 15$).

Method	Uncertainty in k_p - 20%			Uncertainty in τ - 20%			Uncertainty in θ- 20%		
	ITAE	TV	Overshoot	ITAE	TV	Overshoot	ITAE	TV	Overshoot
CC method	6542	1.9381	15.3	1661	1.9381	7.4	13980	1.9381	14.4
ZN method	1414	1.4024	7.4	2563	1.4024	5.3	2416	1.4024	9.5
Proposed method	734.2	0.7926	1.3	1108	0.7926	0.3	1015	0.7926	1.3

a dynamic step test to determine the process parameters using [26]. Secondly, real-time implementation of different controller settings to evaluate the effectiveness of the proposed controller.

Firstly, the standard step test has conducted on the TC Lab device [25] and found FOPTD parameters using [26] are $K = 6.55, \tau = 140, \theta = 15$, for the present method the PID controller settings are $K_c = 0.7926, K_i = 0.0056, K_d = 0.9988$. The PID controller setting by Ziegler's Nicholas method are $K_c = 1.4010, K_i = 0.0486, K_d = 10.1047$, and PID controller setting by Cohen Coon method are $K_c = 1.9381, K_i = 0.0548, K_d = 10.3694$. For a unit set point change in the process, the closed loop performance is plotted in Fig. 12. The proposed method results has been compared with Ziegler's Nicholas method, and Cohen Coon method. The comparison results shows that the proposed method gave smooth and better closed loop control performance in terms of settling time, and overshoot, and error analysis which is listed in the Table 9. Robustness is assessed by performing the uncertainties in the process model parameters. However, the PID controller settings used were the same. Fig. 13 shows the 20% uncertainties in the process model parameters. The proposed method still shows better closed loop control performance. The corresponding errors, overshoot and total variation listed in Table 10.

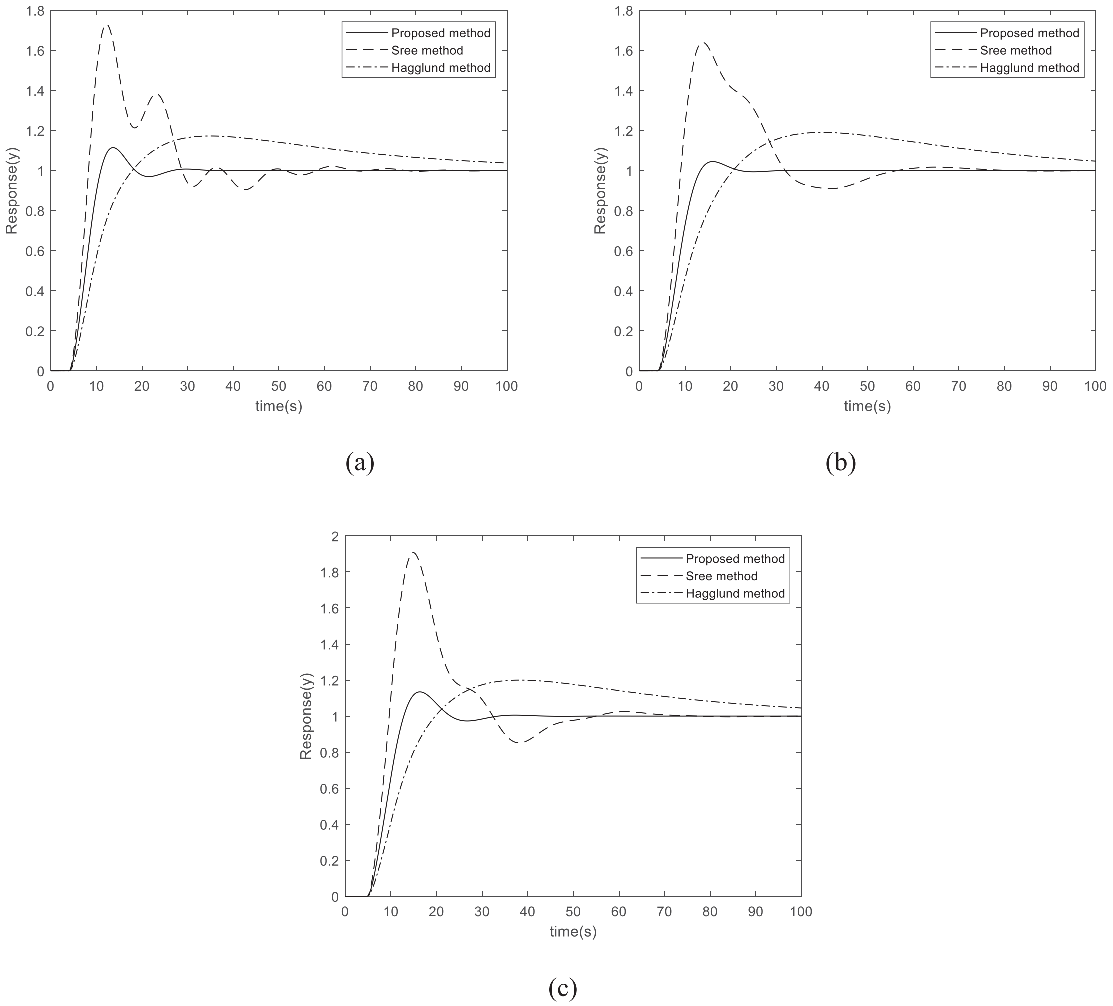


Fig. 8. Setpoint tracking under 20% parameter uncertainty for example 3. ($k = 1, \tau = 1, \theta = 4$) (a) Uncertainty in K (b) Uncertainty in τ (c) Uncertainty in θ.

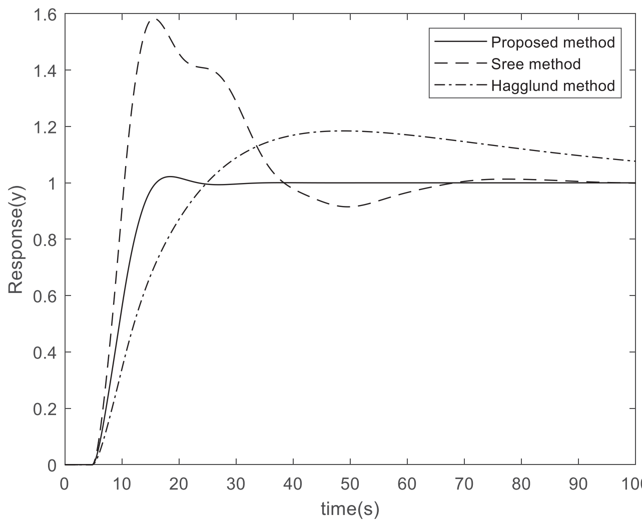
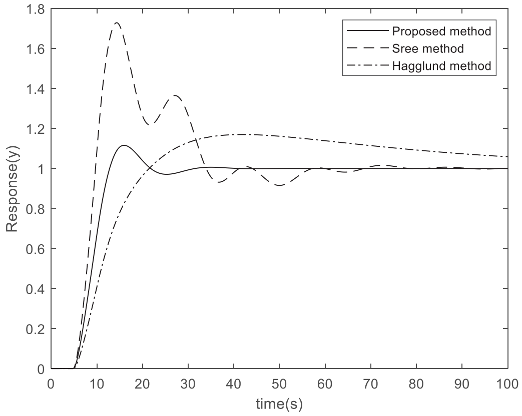
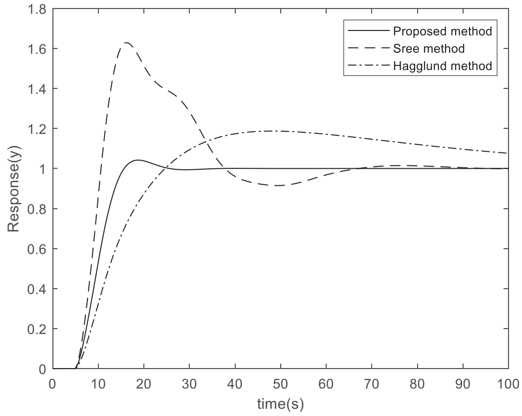


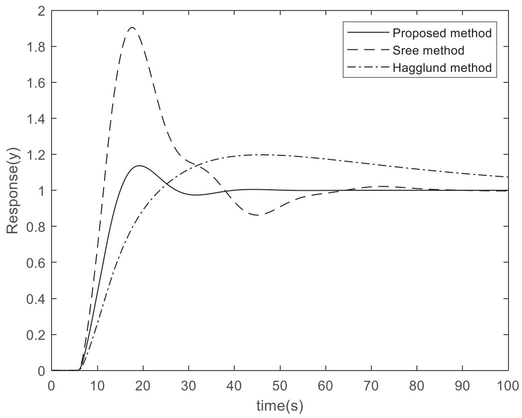
Fig. 9. Setpoint tracking response for a unit step change in example 4($k = 1.2, \tau = 1, \theta = 4.8$).



(a)



(b)



(c)

Fig. 10. Setpoint tracking under 20% parameter uncertainty, for example 4 ($k = 1.2, \tau = 1, \theta = 4.8$). (a) Uncertainty in K (b) Uncertainty in τ (c) Uncertainty in θ.

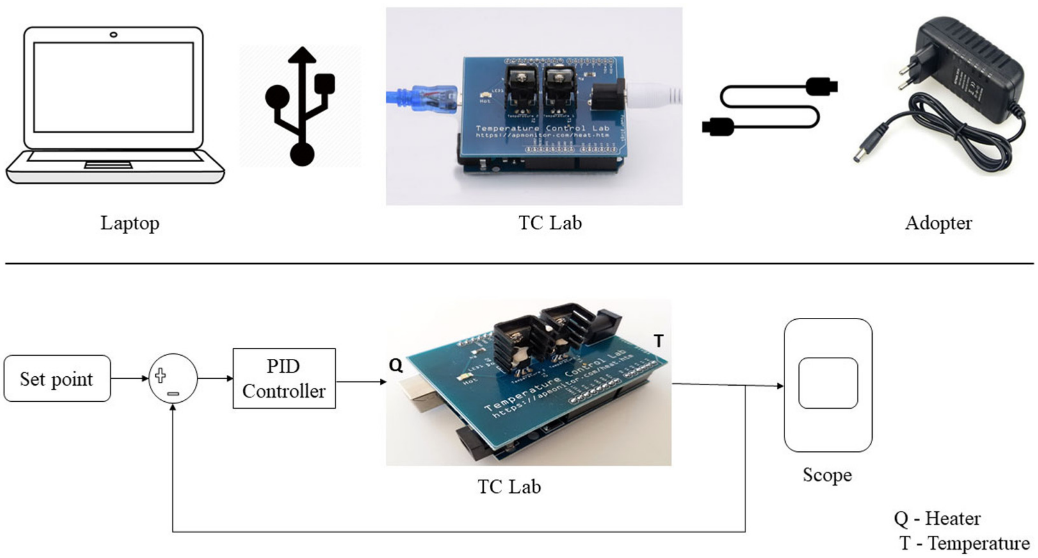


Fig. 11. Temperature control lab setup.

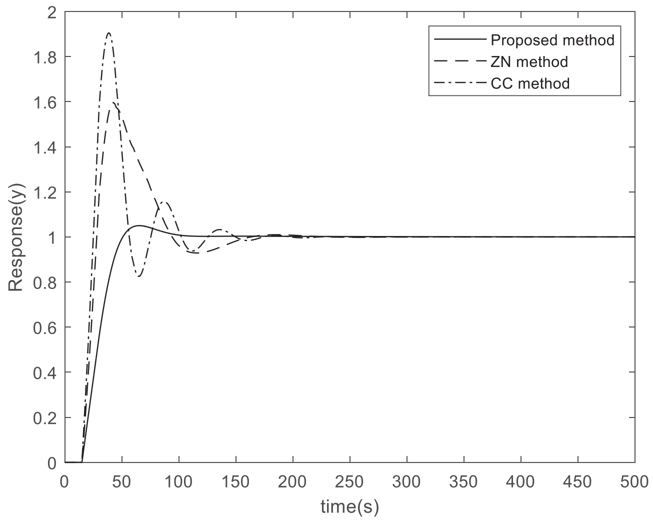


Fig. 12. Setpoint tracking response for unit step change for the identified process ($k = 6.55, \tau = 140, \theta = 15$).

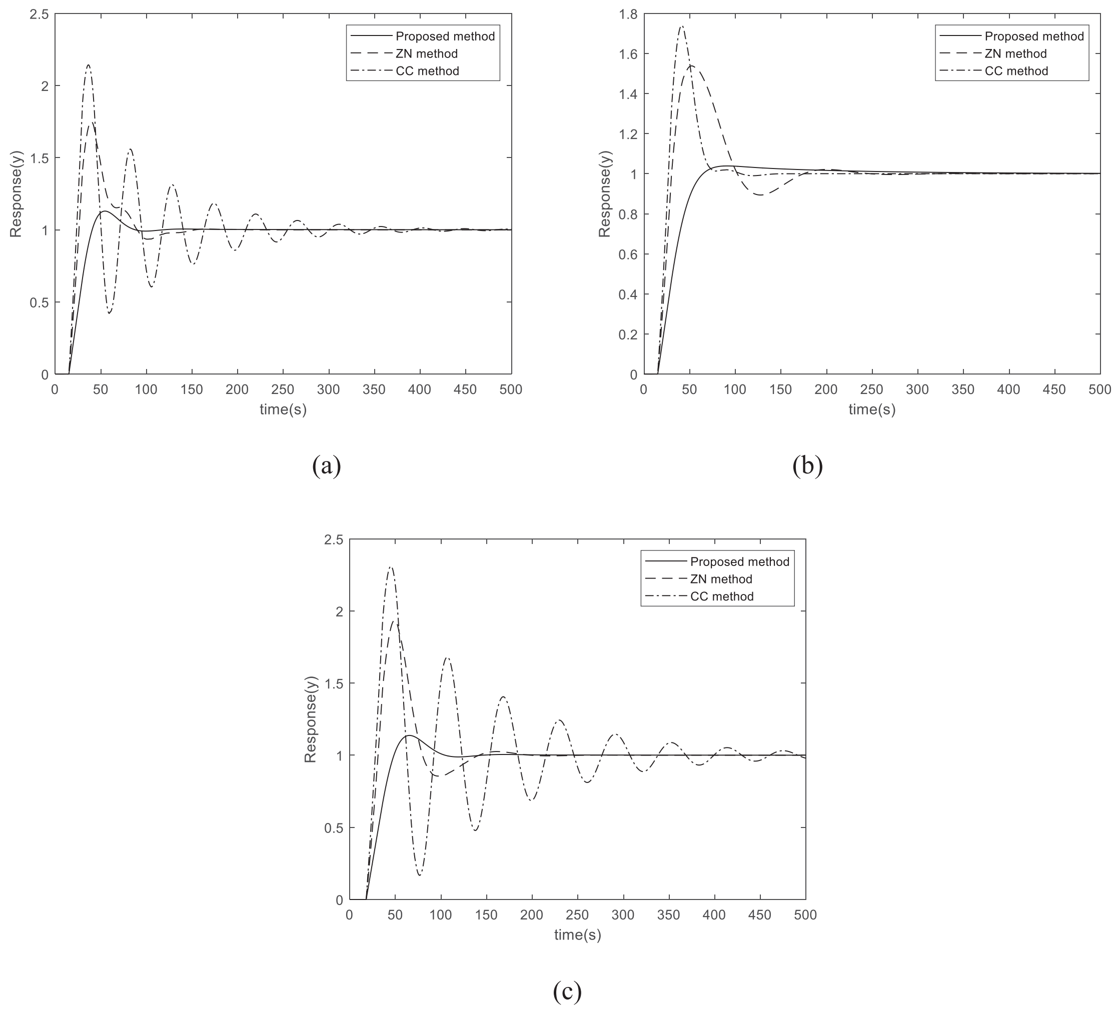


Fig. 13. Setpoint tracking under 20% parameter uncertainty for identified process ($k = 6.55, \tau = 140, \theta = 15$). (a) Uncertainty in K (b) Uncertainty in τ (c) Uncertainty in θ.

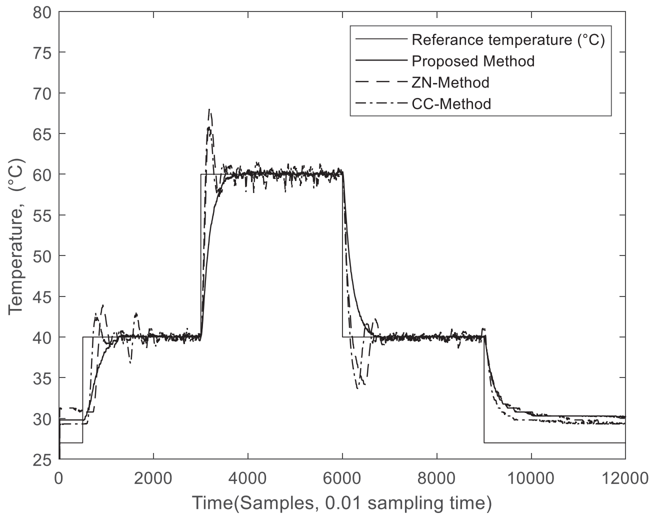


Fig. 14. Temperature tracking response: Real-time implementation of different controller settings on TC lab.

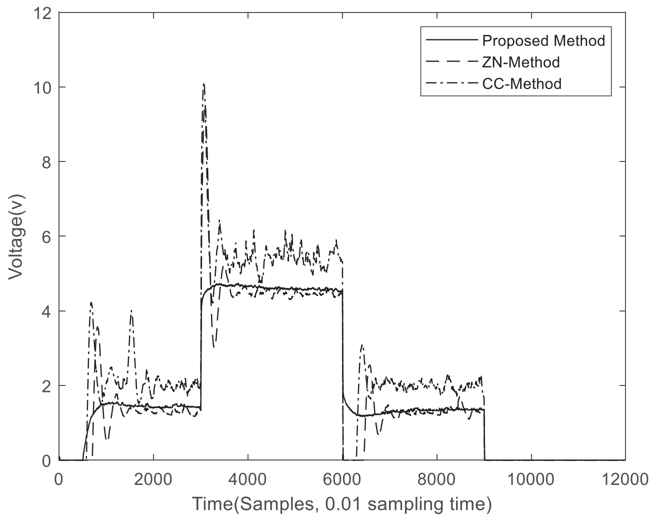


Fig. 15. Manipulating variable versus time behavior: Real-time implementation of different controller settings on TC lab.

Secondly, real-time implementation has been performed to evaluate the controller's closed-loop performance and experimental validation of proposed PID controller settings (Ziegler's Nicholas, Cohen Coon, and Proposed). Fig. 14 shows a comparison set point tracking response between the proposed Ziegler's Nicholas and Cohen Coon methods by changing the temperature in a sequence. The proposed method shows better control performance in overshoot and setting time than the other methods. Fig. 15 shows the corresponding process behavior. Hence, by simulation and real-time implementation results, the proposed method gave the controller's superior closed loop performance compared with other methods reported earlier in the literature.

5. Conclusion

Tuning free PID controller settings were proposed for FOPTD and FOLIPD models for setpoint tracking applications. The closed-loop control performance (errors, total variation, and overshoot) substantiates the proposed PID settings better than other methods reported earlier in the literature. Post introduction of uncertainties in the process model parameters validates the proposed method's robustness. Experimental verification of proposed PID controller settings results validates the proposed method is robust and preferable. The proposed method's advantages were tuning free, explicitly uses the process model, and easy to use.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Authors greatly acknowledge the computational facilities and simulation tools provided through Faculty Seed Research Grant 2019, by National Institute of Technology Calicut.

Appendix. Finding σ value for FOPTD and FOLIPD systems

Finding the σ value for FOPTD system

The value of σ calculated by using α ($\alpha_1 = 1, \alpha_2 = 0.5, \alpha_3 = 0.15, \alpha_4 = 0.03$) values from the reference model [1].

The following equation is obtained after substituting the α values in Eq. (17)

$$0 = -0.005\sigma^3 + 0.1\sigma^2(\tau + \theta) - 0.5\sigma\left(0.5\theta^2 + \tau\theta\right) + 0.1667\theta^3 + 0.5\tau\theta^2$$

Dividing equation above on both sides with τ^3

$$0 = -0.005\left(\frac{\sigma}{\tau}\right) + 0.1\left(\frac{\sigma}{\tau}\right)\left(1 + \frac{\theta}{\tau}\right) - 0.5\left(\frac{\sigma}{\tau}\right)\left(0.5\left(\frac{\theta}{\tau}\right)^2 + \frac{\theta}{\tau}\right) + 0.5\left(\frac{\theta}{\tau}\right)^2 + 0.1667\left(\frac{\theta}{\tau}\right)^3$$

By changing the value of θ/τ from 0 to 10. Corresponding values for σ/τ can be obtained. Which were plotted as show in Fig. 1.

The plotted figure in the form of straight line $y = mx + c$, where $y = \frac{\sigma}{\tau}, x = \frac{\theta}{\tau}$. Substituting the value of slop in the equation gives $\sigma = 1.34520\theta + 0.0504\tau$.

Finding the σ value for FOLIPD system

The value of σ calculated by using α ($\alpha_1 = 1, \alpha_2 = 0.5, \alpha_3 = 0.15, \alpha_4 = 0.03$) values from the reference model [1].

The following equation is obtained after substituting the α values in Eq. (26)

$$0 = 0.5\sigma(\tau + \theta) + 0.5\theta^2 + \tau\theta - 0.15\sigma^2 + 0.25\sigma^2$$

Dividing the above equation on both sides with τ^2

$$0 = 0.1\left(\frac{\sigma}{\tau}\right)^2 - 0.5\left(\frac{\sigma}{\tau}\right) - 0.5\left(\frac{\sigma}{\tau}\right)\left(\frac{\theta}{\tau}\right) + 0.5\left(\frac{\sigma}{\tau}\right)\left(\frac{\theta}{\tau}\right)^2$$

By changing the value of θ/τ from 0 to 10. Corresponding values for σ/τ can be obtained. Which were plotted as show in Fig. 2.

The plotted figure in the form of straight line $y = mx + c$, where $y = \frac{\sigma}{\tau}, x = \frac{\theta}{\tau}$. Substituting the value of slop in the equation gives $\sigma = 1.48320\theta + 0.415\tau$.

References

[1] Shigemasa T, Takagi Y, Ichikawa Y, Kitomori T. A practical reference model for control system design. Trans Soc Instrum Control Eng 1983;19(7):592–4. http://dx.doi.org/10.9746/sicetr1965.19.592.

[2] Skogestad S. Simple analytic rules for model reduction and PID controller tuning. J Process Control 2003;13(4):291–309. http://dx.doi.org/10.1016/S0959-1524(02)00062-8.

[3] Rivera DE, Morarl M, Skogestad S. Internal model control: Pid controller design. Ind Eng Chem Process Des Dev 1986;25(1):252–65. http://dx.doi.org/10.1021/i200032a041.

[4] Horn IG, Arulandu JR, Gombas CJ, Vanantwerp JG, Braatz RD. Improved filter design in internal model control. Ind Eng Chem Res 1996;35(10):3437–41. http://dx.doi.org/10.1021/ie9602872.

[5] Lee Y, Park S, Lee M, Brosilow C. PID Controller tuning for desired closed-loop responses for SI/SO systems. AIChE J 1998;44(1):106–15. http://dx.doi.org/10.1002/aic.690440112.

[6] Shamsuzzoha M, Lee M. IMC - PID Controller design for improved disturbance rejection of time-delayed processes. Ind Eng Chem Res 2007;46(7):2077–91. http://dx.doi.org/10.1021/ie0612360.

[7] Skogestad S. Simple analytic rules for model reduction and PID controller tuning. Model Identif Control 2004;25(2):85–120. http://dx.doi.org/10.4173/mic.2004.2.2.

[8] Vivek S, Chidambaram M. An improved relay auto-tuning of PID controllers for critically damped SOPTD systems. Chem Eng Commun 2012;199(11):1437–62. http://dx.doi.org/10.1080/00986445.2012.668863.

[9] Chen D, Seborg DE. PI/PID controller design based on direct synthesis and disturbance rejection. Ind Eng Chem Res 2002;41(19):4807–22. http://dx.doi.org/10.1021/ie010756m.

[10] Martin J, Corripio AB, Smith CL. How to select controller modes and tuning parameters from simple process models. ISA Trans 1976;15(4):314–9.

[11] Ziegler JG, Nichols NB. Optimum settings for automatic controllers. ASME Trans 1942;42(6):94–100.

[12] Åström KJ, Hägglund T, Hang CC, Ho WK. Automatic tuning and adaptation for PID controllers - a survey. Control Eng Pract 1985;1(4):699–714. http://dx.doi.org/10.1016/0967-0661(93)91394-C.

[13] Cohen GH, Coon GA. Theoretical consideration of retarded control. Trans ASME 1953;75:827–34.

[14] Besharati Rad A, Lo WL, Tsang KM. Self-tuning PID controller using Newton–Raphson search method. IEEE Trans Ind Electron 1997;44(5):717–25. http://dx.doi.org/10.1109/41.633479.

[15] Koivo HN, Tanttu JT. Tuning of PID controllers: Survey of SISO and MIMO techniques. In: IFAC symposia series. vol. 7, 1991, p. 75–80. http://dx.doi.org/10.1016/s1474-6670(17)51299-9.

[16] Ruano AEB, Fleming PJ, Jones DI. Connectionist approach to PID auto-tuning. IEE Proc D Control Theory Appl 1992;139(3):279–85. http://dx.doi.org/10.1049/ip-d.1992.0037.
[17] Aguirre LA. PID Tuning based on model matching. Electron Lett 1992;28(25):2269–71. http://dx.doi.org/10.1049/el:19921460.
[18] Porter B, Jones AH. Genetic tuning of digital PID controllers. Electron Lett 1992;28(9):843–4. http://dx.doi.org/10.1049/el:19920533.
[19] Leva A. Pid auto-tuning algorithm based on relay feedback. IEE Proc D Control Theory Appl 1993;140(5):328–38. http://dx.doi.org/10.1049/ip-d.1993.0044.
[20] Visioli A. Tuning of PID controllers with fuzzy logic. IEEE Proc Control Theory Appl 2001;148(1):1–8. http://dx.doi.org/10.1049/ip-cta:20010232.
[21] Cominos P, Munro N. PID Controllers: Recent tuning methods and design to specification. IEEE Proc Control Theory Appl 2002;149(1):46–53. http://dx.doi.org/10.1049/ip-cta:20020103.
[22] Lennartson B, Kristiansson B. Evaluation and tuning of robust PID controllers. IET Control Theory Appl 2009;3(3):294–302. http://dx.doi.org/10.1049/iet-cta:20060450.
[23] Sree R, MC. Control of unstable systems. Alpha Science Int'l Ltd; 2006.
[24] Astrom KJ, TH. Advanced PID controllers. Instrument Society of America; 2006.
[25] Park J, Martin RA, Kelly JD, Hedengren JD. Benchmark temperature microcontroller for process dynamics and control. Comput Chem Eng 2020;135:106736. http://dx.doi.org/10.1016/j.compchemeng.2020.106736.
[26] Sundaresan KR, Krishnaswamy PR. Estimation of time delay time constant parameters in time, frequency, and Laplace domains. Can J Chem Eng 1978;56(2):257–62. http://dx.doi.org/10.1002/cjce.5450560215.