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A Novel PID Controller Augmented with 2/3 Order Filter for Stable and Integrating Processes with Dead Time

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Abstract: The Effective control of integrating processes with dead time is always a challenging task. Many researchers have addressed this by proportional-integral-derivative (PID) controllers derived through various procedures such as internal model control (IMC), Direct synthesis etc. This paper presents the design of PID controller associated with a 2/3 order filter for integrating processes with dead time. In this study, a polynomial technique is used to obtain the PID parameters and filter coefficients. The maximum sensitivity (MS) criteria is utilized for the selection of the tuning parameter. Second-order Pade's approximation is utilized for dead time approximation. To bring down the overshoot and obtain faster settling time of servo response, a set point filter is employed. The set point filter provides manipulation of servo response without altering regulatory performance. Simulation studies are carried out on some of the bench marking process models used in the literature. The developed control design provides ameliorated closed-loop performance, particularly in terms of disturbance rejection. The proposed controller is relatively robust which is evidenced by performance metrics.

Keywords: PID controller, Integrating processes, Pade's second order approximation, Maximum sensitivity.

1. Introduction

Integrating processes or non-self regulating are the processes which are characterized by transfer functions having at least one pole at the origin [1]. When compared to inherently stable processes, developing controller for non-self-regulating processes is involves intricacy. The complexity aggravates with the presence of dead time. In general, integrating processes are classified as: Integrating first order process with dead time (IFOPDT), Integrating first order process with dead time with positive/negative zero, pure integrating process with dead time (PIPDT), double integrating process with dead time (DIPDT) etc. Examples of such processes are regulating bottom level of a distillation column, monitoring level of a tank with a motor fixed at outlet, DC motor that is controlled by current, take-off dynamics of a spacecraft, controlled drying in paper industry continuous stirred tank reactor (CSTR) with exothermic reactor, etc. PID controllers are extensively used in the chemical process industry as they are simpler to tune, facile to implement. Finding the optimum values of controller parameters such as Proportional gain(k_p), integral time constant(τ_i) and derivative time constant(τ_d) is crucial. Sundry methods have been used to estimate the controller parameters such as Z-N method [2], Coohen-coon method [3], Smith predictor based control [4], internal model control (IMC) [5] etc.

As an effective solution to handle integrating process with dead time, various PI and PID controller design techniques [6-8] have been proposed earlier. IMC has also gained widespread acceptance in chemical industries as it makes tuning simple with single tuning parameter [9]. However, due to the circumscriptions imposed by dead time on system performance and stability, controlling large dead time-associated processes is arduous [10]. In order to amend the performance, modified IMC structures have been proposed by various authors [1, 11, 12]. Further, it is also proposed to reinforce IMC-PID method by utilizing fractional filter [13-15]. Several other methods with some homogeneous attributes and diversities have withal been studied such as Direct synthesis method [10, 16], Equating co-efficient method [17], Two degree of freedom(2DOF) control scheme [18, 19], optimization methods [20, 21]. Several researchers have additionally suggested the multi-loop feedback control structures [22, 23]. There are certain stand-alone advantages and disadvantages in employing these strategies. The conventional Smith predictor control techniques fail to provide stable performance for integrating process with dead time. A significant number of research findings on modified smith predictor have been reported to address this problem [24-26]. These modified smith predictor control designs are intricate as they necessitate more number of controllers. The PID controller with the second order filter designed by polynomial method is proposed in [27] for controlling integrating processes.

A review of the literature specifies that it is still scoped to enhance the PID controller's performance and robustness for integrating processes.

1.1 Key research gaps

- Many existing works limit themselves to first-order time delay approximation when it comes to time delay approximation.
- Adding a filter to PID improves the performance of PID. However, the majority of the existing works have done this with a first-order filter.
- The existing works in the literature are limited to first-order filters probably because of mathematical complexity when it is tried to incorporate higher order time delay and higher order filters.
- For control of integrating processes with dead time, some of the existing strategies used multi-loop controllers. The multi-loop controllers are intricate and required multiple tuning parameters to tune. The single loop control structure is easy to analyze and tune.

1.2 Key contributions of the research work

- In this paper, a single loop control structure with PID controller associated with 2/3 order filter is proposed based on the polynomial method for stable and integration process with dead time.
- The current control technique employed a second-order Pade's time delay approximation for enhanced performance for the provided accuracy in time-delay.

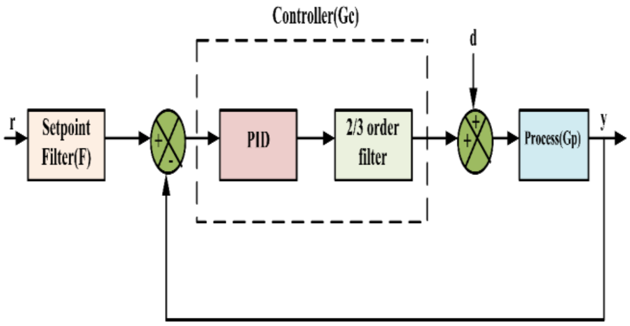

Figure. 1 Proposed controller

- The selection of parameters of PID controller is based on the Maximum Sensitivity(MS) criteria and they are derived using a single tuning parameter.
- The proposed technique also verified on a real-time experimental setup for practical applicability.

The present paper is structured as follows: section 2 interprets the mathematical analysis for the suggested controller design, section 3 presents simulation results and discussion, and Section 4 discusses the paper's conclusion.

2. Mathematical analysis of the proposed controller

2.1 Controller design

The proposed controller structure is depicted in Fig. 1. From Fig. 1, r represents the set point, F represents the set point filter, G_c represents the controller, G_p represents a process to be controlled and y, d are the output and disturbance signals respectively. The servo and regulatory transfer functions are expressed in Eq. (1) and Eq. (2) respectively.

$$\frac{y}{r} = \frac{FG_cG_p}{1+G_cG_p} \tag{1}$$

$$\frac{y}{d} = \frac{G_p}{1+G_cG_p} \tag{2}$$

A PID controller cascaded with 2/3 order is proposed for DIPDT and IFOPDT is represented in Eq. (3).

$$G_c = \left(k_p + \frac{k_i}{s} + k_d s\right)\frac{(Z_2s^2+Z_1s+1)}{(p_2s^2+p_1s+1)(p_3s+1)} \tag{3}$$

$$\frac{y}{r}=\frac{F(k_ds^2+k_ps+k_i)(z_2s^2+z_1s+1)k(1-\frac{s\theta}{2})}{s(p_2s^2+p_1s+1)(p_3s+1)(\tau s+1)(1+\frac{s\theta}{2})+k(k_ds^2+k_ps+k_i)(z_2s^2+z_1s+1)(1-\frac{s\theta}{2})} \quad (5)$$

$$\frac{y}{d}=\frac{ks(p_2s^2+p_1s+1)(p_3s+1)e^{-s\theta}}{s^2(p_2s^2+p_1s+1)(p_3s+1)(\tau s+c)+k(k_ds^2+k_ps+k_i)(z_2s^2+z_1s+1)e^{-s\theta}} \quad (6)$$

2.2 Controller(G_c) design for DIPDT and IFOPDT

The process is represented in Eq. (4)

$$G_p=\frac{k}{s(\tau s+c)}e^{-s\theta} \quad (4)$$

For DIPDT, $c=0$ and $\tau=1$. For IFOPDT, $c=0$ and $\tau>0$. By using Eqs. (1), (2), (3) and (4), the obtained Eq. (5) represents servo and Eq. (6) indicates the regulatory transfer functions respectively.

Eq. (7) represents the characteristic equation (CE).

$$CE=s^2(p_2s^2+p_1s+1)(p_3s+1)(\tau s+c)+k(k_ds^2+k_ps+k_i)(z_2s^2+z_1s+1)e^{-s\theta} \quad (7)$$

It is customary to solve the CE against the desired CE using appropriate dead time approximation to retrieve the unknown parameters. Pade's first-order approximation is the most predominantly used approximation ([11, 12]). To achieve even more accuracy, the current work used a Pade's second-order approximation and it is represented in Eq. 8.

$$e^{-s\theta}=\frac{(1-(\theta s/2)+s^2\theta^2/12)}{(1+(\theta s/2)+s^2\theta^2/12)} \quad (8)$$

By employing approximation of Pade's second order and considering $z_2=\frac{\theta^2}{12}$ and $z_1=\frac{\theta}{2}$ and substituting in Eq. (7), the resultant CE is represented in Eq. (9).

$$CE=s^2(p_2s^2+p_1s+1)(p_3s+1)+k\left(k_ds^2+k_ps+k_i\right)\ (1-(s\theta\ /\ 2)+(s^2\theta^2\ /\ 12)) \quad (9)$$

Further simplification of Eq. (9) leads to

$$\left.\begin{aligned} c_6s^6+c_5s^5+c_4s^4+c_3s^3+c_2s^2+c_1s+1=0\\ c_6=\frac{p_2p_3\tau}{kk_i}\\ c_5=\frac{p_2(\tau+cp_3)+p_1p_3\tau}{kk_i}\\ c_4=\frac{\frac{kk_d\theta^2}{48}+cp_2+p_3\tau+p_1(\tau+cp_3)}{kk_i}\\ c_3=\frac{\frac{kk_p\theta^2}{48}-\frac{kk_d\theta}{4}+\tau+cp_1+cp_3}{kk_i}\\ c_2=\frac{\frac{kk_i\theta^2}{48}-\frac{kk_p\theta}{4}+c+kk_d}{kk_i}\\ c_1=\frac{kk_p-\frac{kk_i\theta}{4}}{kk_i} \end{aligned}\right\} \quad (10)$$

Eq. (10) is to be solved against the desired CE to get the unknown PID and filter parameters. In the present study, the assumed desired CE is shown in Eq. (11).

$$(\lambda s+1)^3(1+sz_1+s^2z_2)(p_3s+1)=0 \quad (11)$$

Where λ is the tuning parameter. The reason behind the selecting target CE with multiple poles is not empirical. It is evident from servo and regulatory responses that the controller is inserting the zeros in the transfer functions of servo and regulatory responses, which may enforce overshoot/undershoot. The selected target CE will be able to cancel out some of these zeros and allows the remaining poles to be located at $s=-\left(\frac{1}{\lambda}\right)$.

2.3 Controller(G_c) design for stable first order process with dead time(FOPDT)

The considered process is represented in Eq. (12)

$$G_p(s)=\frac{k}{\tau s+1}e^{-s\theta} \quad (12)$$

From the Pade's first order time delay approximation, the delay represented in Eq. (13).

$$e^{-s\theta}=\frac{1-(\frac{s\theta}{2})}{1+\frac{s\theta}{2}} \quad (13)$$

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$$\frac{y}{r}=\frac{F(k_d s^2+k_p s+k_i)(z_2 s^2+z_1 s+1)k(1-\frac{s\theta}{2})}{s(p_2 s^2+p_1 s+1)(p_3 s+1)(\tau s+1)(1+\frac{s\theta}{2})+k(k_d s^2+k_p s+k_i)(z_2 s^2+z_1 s+1)(1-\frac{s\theta}{2})} \quad (14)$$

$$\frac{y}{d}=\frac{ks\left(1-\frac{s\theta}{2}\right)(p_2 s^2+p_1 s+1)(p_3 s+1)}{s(p_2 s^2+p_1 s+1)(p_3 s+1)\left(1+\frac{s\theta}{2}\right)(\tau s+1)+k\left(k_d s^2+k_p s+k_i\right)(z_2 s^2+z_1 s+1)\left(1-\frac{s\theta}{2}\right)} \quad (15)$$

The controller structure for stable FOPDT is same as Eq. (3). Substituting Eq. (3) and Eq. (12) in Eqs. (1) and (2) results in servo and regulatory transfer functions as represented in Eqs. (14) and (15) respectively.

Eq. (16) represents the CE.

$$s(p_2 s^2+p_1 s+1)(p_3 s+1)(1+\frac{s\theta}{2})(\tau s+1)+k(k_d s^2+k_p s+k_i)(z_2 s^2+z_1 s+1)(1-\frac{s\theta}{2})=0 \quad (16)$$

The modified form of CE represented in Eq. (17). Here $(1-\frac{s\theta}{2})$ is represented as a $e^{-\frac{s\theta}{2}}$ using first-order series approximation.

$$s(p_2 s^2+p_1 s+1)(p_3 s+1)(1+\frac{s\theta}{2})(\tau s+1)+k(k_d s^2+k_p s+k_i)(z_2 s^2+z_1 s+1)e^{-s\theta/2}=0 \quad (17)$$

To represent the dead time, Pade's second-order dead time approximation is utilized. The dead time representation of $e^{-\frac{s\theta}{2}}$ is represented in Eq. (18).

$$e^{-s\theta/2}=\frac{(1-(\theta s/4)+s^2\theta^2/48)}{(1+(\theta s/4)+s^2\theta^2/48)} \quad (18)$$

The CE is further simplified by considering $z_2=\frac{\theta^2}{48}$ and $z_1=\frac{\theta}{4}$ and it is represented in Eq. (19).

$$s(p_2 s^2+p_1 s+1)(p_3 s+1)(\tau s+1)\left(1+\frac{s\theta}{2}\right)+k(k_d s^2+k_p s+k_i)(1-\frac{\theta s}{4}+\frac{\theta^2 s^2}{48})=0 \quad (19)$$

Further simplification of Eq. (19) leads to

$$\left.\begin{array}{c}
c_6 s^6+c_5 s^5+c_4 s^4+c_3 s^3+c_2 s^2+c_1 s+1=0\\
c_6=\dfrac{p_2 p_3 \tau\theta}{2kk_i}\\
c_5=\dfrac{p_2\left(\frac{\theta(p_3+\tau)}{2}+p_3\tau\right)+\frac{p_1 p_3\tau\theta}{2}}{kk_i}\\
c_4=\\
\dfrac{p_1\left(\frac{\theta(p_3+\tau)}{2}+p_3\tau\right)+p_2\left(p_3+\tau+\frac{\theta}{2}\right)+\frac{kk_d\theta^2}{48}+\frac{p_3\tau\theta}{2}}{kk_i}\\
c_3=\\
\dfrac{p_2+\frac{\theta(p_3+\tau)}{2}+p_3\tau+p_1\left(p_3+\tau+\frac{\theta}{2}\right)+\frac{kk_p\theta^2}{48}-\frac{kk_d\theta}{4}}{kk_i}\\
c_2=\dfrac{p_1+p_3+\tau+\frac{\theta}{2}+kk_d+\frac{kk_i\theta^2}{48}-\frac{kk_p\theta^2}{4}}{kk_i}\\
c_1=\dfrac{kk_p-\frac{kk_i\theta}{4}+1}{kk_i}
\end{array}\right\} \quad (20)$$

In order to find out the unknown parameters, Eq. (20) is solved against the desired CE which is same as Eq. (11).

2.4 Setpoint filtering

In the present work, some of the controller inserted zeros in servo and regulatory transfer functions are compensated by clever selection of target CE. However, there are still some zeros left. Pertaining to servo response, the effect zeros introduced by the controller can be cancelled out by either set point filter or set point weighting. In this study, analytically designed setpoint filter is applied. The suggested setpoint filter(F) in servo response is intended to counteract the controller inserted zeros. The mathematical form of F is represented in Eq. (21).

$$F=\frac{\gamma s+1}{(\frac{k_d}{k_i}s^2+\frac{k_p}{k_i}s+1)} \quad (21)$$

γ is a new variable and has no effect on a closed-loop system's stability as it stay outside the loop. The parameter that directly influences the internal stability of the system is λ. The choosing of λ plays a vital role in the controller design.

2.5 Selection of λ

The choice of λ is significant because it is closely associated with the closed-loop system's stability. Various authors ([1, 16, 27]) have used MS-based tuning, which characterizes the robust stability of a closed-loop system. Eq. (22) represents the mathematical form of MS.

$$MS = maximum\left(\left|\frac{1}{1+G_c G_p}\right|\right) \tag{22}$$

Where $G_c G_p$ is a loop transfer function (L). The inverse of the shortest distance from the Nyquist plot of the loop transfer function to the critical point is called Maximum Sensitivity (MS) ([1, 12, 27]). The lower MS value will result in higher robust stability [27]. As a compromise between robust stability and speed of response, MS should be set between the range of 1.2 and 2 [27]. However, achieving faster responses with lower MS values is not always viable for integrating and unstable processes.

3. Simulation studies

Simulation analyses are carried out in this section to analyze the suggested method's performance compared to other control techniques in the literature. Eqs. (23) and (24) represent the expressions of several performance indices.

$$Integral\ Square\ Error(ISE) = \int_0^\infty e^2(\tau)\, d\tau \tag{23}$$

$$Integral\ Absolute\ Error(IAE) = \int_0^\infty |e(\tau)| d\tau \tag{24}$$

Where e indicates the error. IAE describes the ability to penalize the oscillations quickly. ISE is a measure of suppressing large errors. The manipulated variable smoothness is measured by total variance (TV). The expression for calculating TV is shown in Eq. (25).

$$Total\ \ Variance(TV) = \sum_{j=0}^{\infty} |u_{j+1} - u_j| \tag{25}$$

Where u_{j+1} and u_j are the process inputs at $(j+1)^{th}$ and j^{th} instants respectively. TV indicates the safety and longevity of final control elements.

3.1 Example 1

The fermentation reactors, current controlled DC motors, and the dynamics of a spacecraft departure are some of the best examples of double-integrating processes. In this example considered DIPDT is represented in Eq. (26).

$$G_p(s) = \frac{1}{s^2} e^{-s} \tag{26}$$

The above process studied previously by [12, 16], [28] and [30] in their control strategies. The current technique is compared with the methods of [16] and [30]. The controller parameters of all the methods are shown in Table 1. All the methods are tuned for Ms of 2 for fair comparison. The suggested technique obtained the MS value 2 at $\lambda = 2.412$. At $t = 0\ sec$ a unit step change is considered as a set point and a unit step change disturbance is considered at $t = 100\ sec$. Fig. 2 depicts the performance waveforms under nominal (No model mismatch) conditions and Table 2 depicts the comparison analysis of both controllers. From Fig. 2 and Table 2, it is evident that under servo response, the suggested technique produced better performance than other two methods in all performance indices but lagged in T.V. In all aspects of the performance indices, the recommended method outperformed the other methods in the disturbance rejection condition.

To test the robust performance, +20% variation in k and $\boldsymbol{\theta}$ are imposed simultaneously. The performance waveforms under the perturbed (Model mismatch) condition are shown in Fig. 3, and the performance matrix of this condition is presented in Table 3. According to Table 3, the proposed method provided better performance in all indices in servo response but lagged in T.V. The superior performance of the proposed method is also observed in disturbance rejection condition compared to [16] and [30] methods except in T.V. The proposed method, even though a single loop control structure, it provides better results as compared with double loop control (I-PD structure) [30].

3.2 Example 2

Examples of IFOPDT include drying operations in the paper industry and the continuous stirred tank reactor (CSTR) with an exothermic reaction. The IFOPDT considered in this example is previously studied by [12], [21] and [29] in their control strategies. The IFOPDT is represented in Eq. (27).

$$G_p(\mathrm{s}) = \frac{0.2}{s(4s+1)} e^{-s} \tag{27}$$

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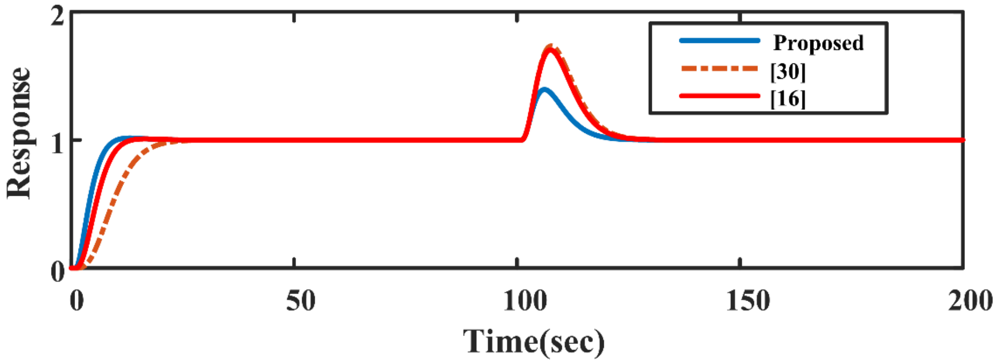
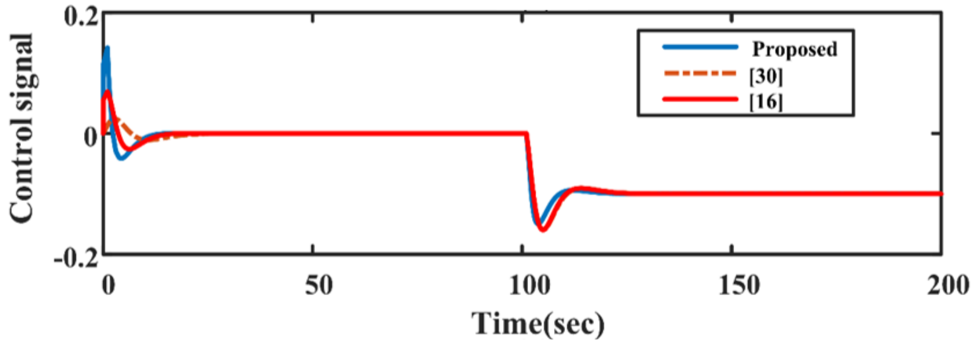
Table 1. Controller parameters for different method

Process	Tuning Method	PID Parameters		
		$\mathbf{k_p}$	$\mathbf{k_i}$	$\mathbf{k_d}$
$\frac{1}{s^2}e^{-s}$	Proposed[a]	0.2335	0.0284	0.7142
	[30][b]	0.1319	0.01323	0.15126
	[16][c]	0.1378	0.0142	0.5265
$\frac{0.2}{s(4s+1)}e^{-s}$	Proposed[d]	7.956	1.2276	14.63
	[21]	8.7596	1.8572	14.692
	[12][e]	5.5068	0.6229	12.06
DC servo motor	Proposed[f]	0.0623	0.3804	0.000942

$f = filter$; $f_R = setpoint\ filter$; **a**: $f = \frac{0.0833s^2+0.5s+1}{0.0001s^3+0.0332s^2+0.1806s+1}$; $f_R = \frac{4.s+1}{25.189s^2+8.236s+1}$;
b: $f = \frac{3.9148s+1}{1.1303s+1}$; **c**: $f = \frac{1.0761s+1}{1.0392s+1}$; $f_R = \frac{3.890ss+1}{37.1655s^2+9.7264s+1}$ **d**: $f = \frac{0.0833s^2+0.5s+1}{0.0001s^3+0.0486s^2+0.2863s+1}$;
$f_R = \frac{5s+1}{27.666s^2+10.9s+1}$; **e**: $f = \frac{0.125s+1}{0.0574s+1}$: $f_R = \frac{0.48s+1}{1.210s+1}$ **f** : $f = \frac{0.001s^2+0.015s+1}{0.0001s^2+0.01375s+1}$;
$f_R = \frac{10s+1}{0.0025s^2+0.1638s+1}$



(a)



(b)

Figure. 2 No model mismatch response of Example 1: (a) Response and (b) Control signal

In this process, the suggested technique is compared with the method of [21] which outperforms the other methods [22, 31] and with the method of [12]. All the methods are compared by tuning the same IAE value in nominal servo condition.

The controller parameters for the three methods are tabulated in Table 1. At $t = 0\ sec$, a step change of magnitude act as a setpoint and a unit disturbance change is applied at $t = 60\ sec$. The performance curves under nominal conditions are shown in Fig. 4 and the performance matrix is shown in Table 2. According to Table 2, it is concluded that the method [21] performed better in case of T.V and settling time. Whereas method [12] provided better values in case of IAE and ISE in servo response. In regulatory response, method [21] performed better response, but lagged in T.V. The suggested control technique

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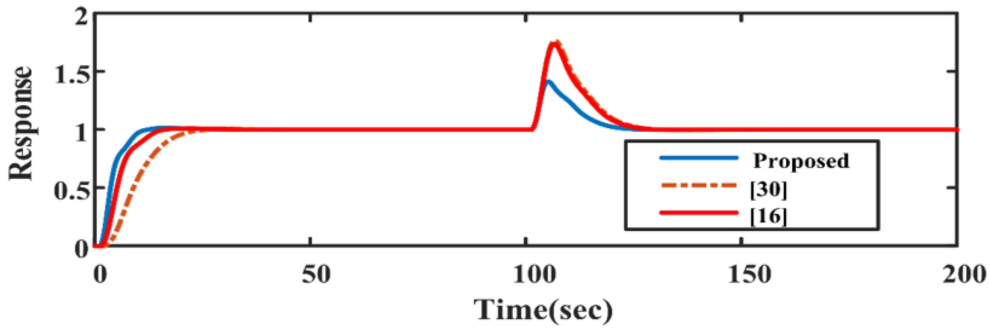
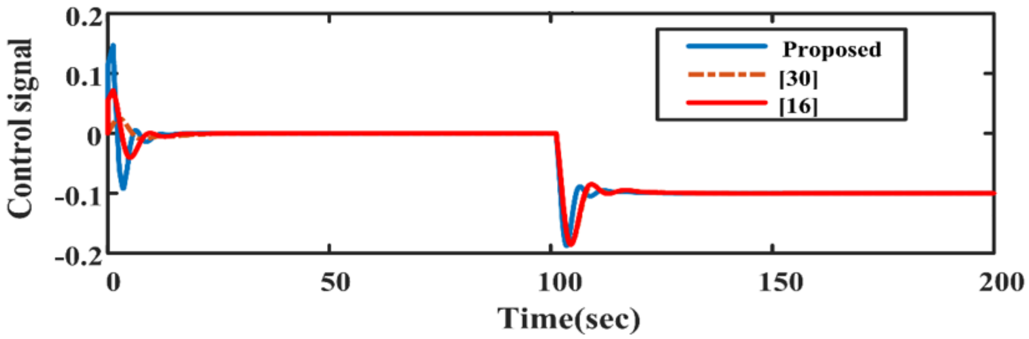


(a)



(b)

Figure. 3 Model mismatch response of Example 1: (a) Response, and (b) Control signal

Table 2. Performance matrices under no model mismatch condition

		Servo				**Regulatory**			
Process	**Tuning Method**	**IAE**	**ISE**	**T.V.**	t_s	**IAE**	**ISE**	**T.V.**	t_s
$\frac{1}{s^2}e^{-s}$	Proposed	4.463	3.218	0.734	9.19	3.527	0.960	0.313	22.81
	[30]	9.964	7.456	0.0705	21.54	7.554	3.87	0.337	25.35
	[16]	5.959	4.43	0.1931	12.053	7.042	3.456	0.3393	24.75
$\frac{0.2}{s(4s+1)}e^{-s}$	Proposed	4.82	3.405	11.85	11.74	1.217	0.125	2.687	20.90
	[21]	4.84	4	9.21	9.39	0.587	0.05	4.696	14.03
	[12]	4.8	2.65	37.5	18.93	1.605	0.188	2.86	25.35

Table 3. Performance matrix under model mismatch condition

		Servo				**Regulatory**			
Process	**Tuning Method**	**IAE**	**ISE**	**T.V.**	t_s	**IAE**	**ISE**	**T.V.**	t_s
$\frac{1.2}{s^2}e^{-1.2s}$	Proposed	4.497	3.137	0.959	10.45	3.538	0.944	0.432	23.24
	[30]	10.05	7.354	0.070	22.16	7.608	3.769	0.407	26.59
	[16]	6.07	4.306	0.242	14.23	7.09	3.366	0.417	25.95
$\frac{0.23}{s(3.4s+1)}e^{-1.15s}$	Proposed	4.829	3.258	14.85	13.19	1.218	0.127	3.467	21.75
	[21]	5.827	3.89	29.74	33.37	1.137	0.07	17.07	55.35
	[12]	4.37	2.53	47.36	19.35	1.60	0.184	4.04	25.6

performed marginally both in servo and regulatory conditions.

To analyse the perturbed performance, +15 % perturbation in k, -15% perturbation in τ, and +15% perturbation in $\boldsymbol{\theta}$ are applied. The resultant performance curves are depicted in Fig. 5 and the comparative study is presented in Table 3. As per Table 3, [12] presented better values in case of IAE and ISE but provided large value of T.V. The proposed method provided comparable performance with method of [12] and provided better T.V. and settling time values in case of servo condition. In regulatory conditions, method [21] provided large oscillations, further increasing the model

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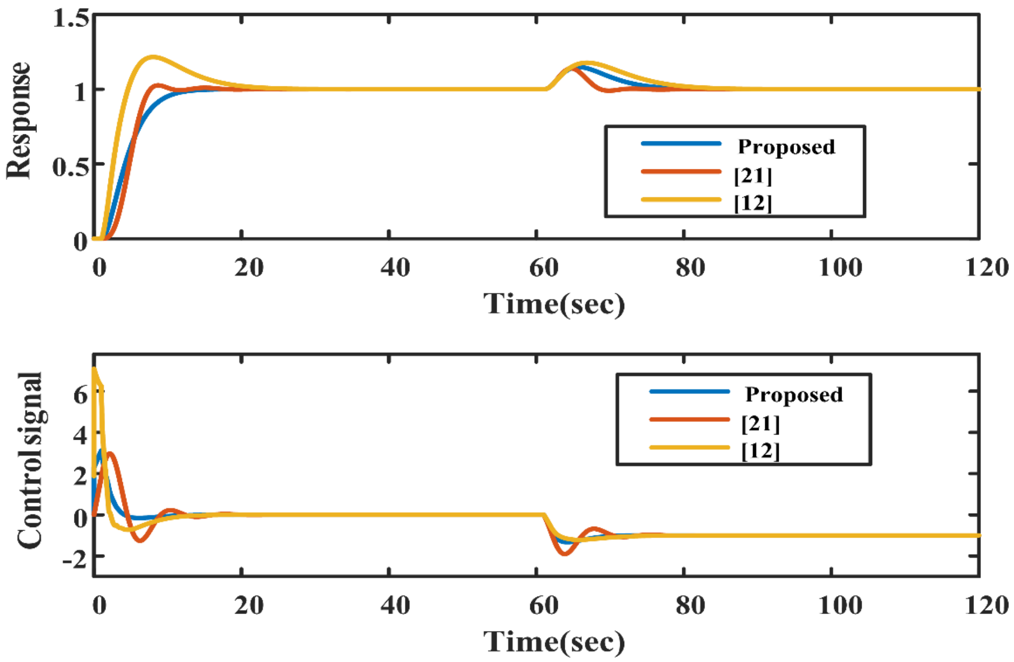

Figure. 4 No model mismatch response of Example 2: (a) Response, and (b) Control signal

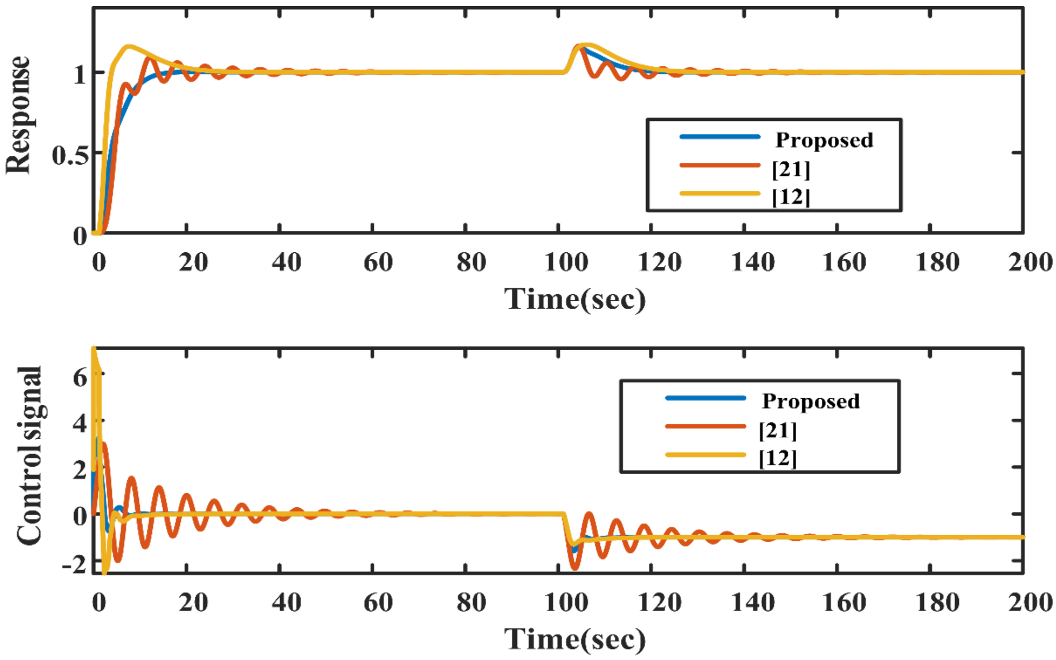

Figure. 5. Model mismatch response of Example 2: (a) Response (b) Control signal

uncertainties, it provided unstable performance. The proposed method provided superior performance even in the case increment in model uncertainties.

3.3 Hardware results and discussion

To test the validity of the proposed control technique in a practical implementation, the suggested controller has been put to test the control of the speed of the DC servo motor. DC servo motors are often used in various industrial applications, including automotive, robotics, and manufacturing. The ability of the closed-loop system to track the reference trajectory is one of the real-time issues in servo operation. A Quanser QUBE rotary servo system is considered in this work. This system provides experimental flexibility and software compatibility for testing and validating the control strategies. Fig. 6 depicts the actual experimental bench setup for the Qube DC Servo motor process.

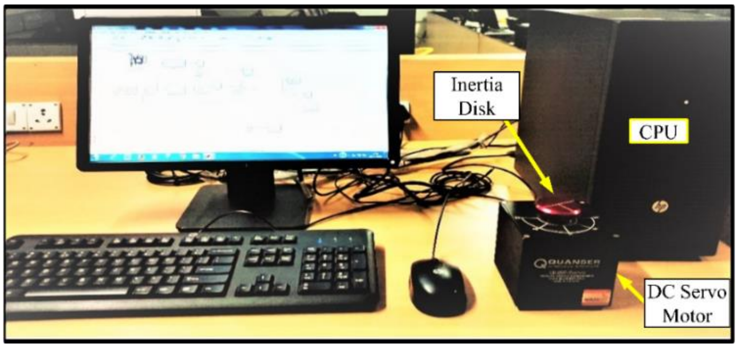

Figure. 6 Experimental test bench of Qube DC Servomotor

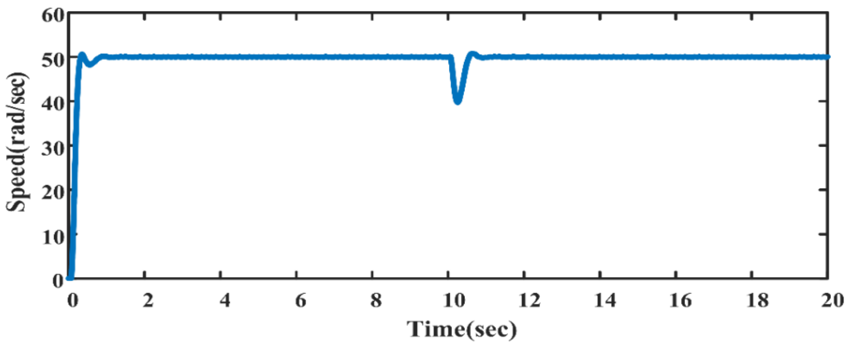

Figure. 7 DC servo motor speed response for a step input

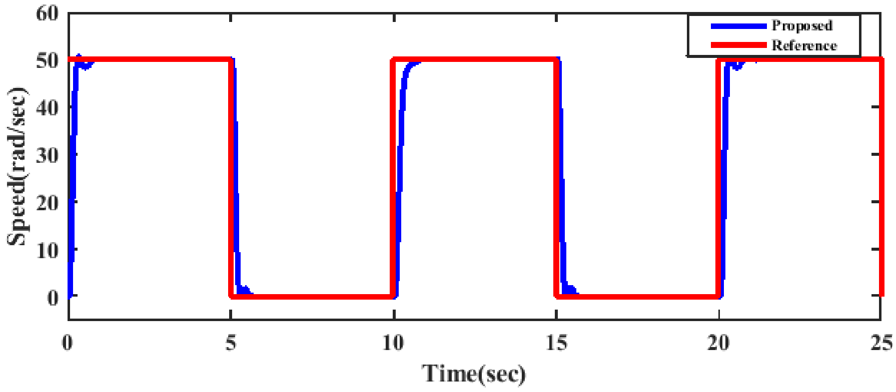

Figure. 8 DC servo motor speed response for a square input

The transfer function estimated from the input-output data for the DC servo motor is represented in Eq. (28).

$$G_p(s) = \frac{24.7523}{(0.1708s+1)} e^{-0.06s} \quad (28)$$

The transfer function is a first-order process. However, the authors have included a time delay in the loop to validate the suggested method. The recommended controller PID parameters are calculated at tuning factor ⋋=0.08 and are listed in Table 1.

To test the set point tracking capabilities, at $t = 0\ sec$, a step input of 50 rad/sec is applied and at $t = 10\ sec$ an inverse step disturbance is considered. The speed response for a step input is depicted in Fig. 7.

A square wave with an amplitude varying from 0 to 50 rad/sec is used to test the set point tracking capabilities. The pulse width is set to 50% and the resulting response is depicted in Fig. 8. It is observed from Figs. 7 and 8, that, the proposed controller is capable of being used for real time processes.

4. Conclusion

This paper discusses the design and analysis of a novel PID controller augmented with a 2/3 order filter for DIPDT and IFOPDT and stable FOPDT. A polynomial approach is utilized to obtain PID controller parameters and filter coefficients. MS based analytical approach is used to obtain the controller tuning parameter (⋋). The second-order

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Pade's approximation is employed for representing the dead time to develop a PID controller. Simulation studies are carried out on different processes to demonstrate the benefits of the proposed controller. The suggested controller outperforms the reported methods in the literature in majority of the performance indices. The present controller is also verified for practical applicability using Quanser DC servo motor. Simulation and experiment results show that cascading 2/3 order filter to PID controller improves tracking performance and also the robustness of the closed loop system to exogenous disturbances and model uncertainty.

Nomenclatures

G_p	Process
G_c	Controller
k	Gain
Z_1, Z_2, P_1, P_2, P_3	Filter constants
k_p	Proportional constant
k_i	Integral constant
k_d	Derivative constant
τ	Time constant of the process
λ	Tuning parameter
γ	Setpoint filter parameter
θ	Time delay

Conflicts of interest

The authors declare no conflict of Interest.

Author contributions

Conceptualization, K.Divakar and M.P.Kumar; methodology, K.Divakar; software and validation, K.Divakar and M.P.Kumar; formal analysis,M.P.Kumar; investigaion, M.P.Kumar; resources, K.Divakar; data curation, M.P.Kumar; writing—original draft preparation, K.Divakar; writing—review and editing, K.Divakar; visualization, K.Divakar and M.P.Kumar; supervision, M.P.Kumar; project administration, M.P.Kumar; funding acquisition, M.P.Kumar.

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