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IMC based PID Controller Tuning of Series Cascade Unstable Systems

K. Ghousiya Begum*, T. K. Radhakrishnan, A. Seshagiri Rao***, M. Chidambaram******

*Department of Chemical Engineering, National Institute of Technology, Tiruchirappalli 620015 INDIA(Tel: +919788530064; e-mail: ghousiyabegum.k@gmail.com).

**Department of Chemical Engineering, National Institute of Technology, Tiruchirappalli 620015 INDIA(e-mail: radha@nitt.edu)

*** Department of Chemical Engineering, National Institute of Technology, Warangal, Telangana 506004 INDIA(e-mail: seshagiri@nitc.ac.in)

**** Department of Chemical Engineering, Indian Institute of Technology, Chennai 600036 INDIA(e-mail: chidam@iitm.ac.in)

Abstract: A simple method of tuning series cascade systems for Integrating, Unstable First order plus time delay process is proposed. Here the PID controller is analyzed for series cascade process based on IMC method and H2 minimization. Maclaurin series is used to approximate the controller expression as a PID controller. Improved closed loop performances are achieved with the proposed method when compared to the recently reported methods in the literature. Further, an analysis is carried out based on maximum sensitivity for arriving at systematic guidelines for selection of the closed loop tuning parameter which is essential for unstable systems. The robustness for uncertainty in the model parameters is studied and compared with that of the controllers reported by Lee et al. (2002).

Keywords: Unstable process, IMC, H2 minimization, PID controller, Cascade process, robustness.

1. INTRODUCTION

Open loop unstable processes are much more difficult to control than stable processes. Although tuning methods were suggested (Rao et al., 2012; Padma Sree et al., 2004), desired performance cannot be obtained with simple PID controllers for unstable systems with large dead times. Smith delay compensation is proven as an effective tool for time delay processes. However, the original Smith predictor is not applicable for unstable systems. It is well known that Cascade control is successful and an alternate method for enhancing the control performance than a single feedback control particularly if the disturbances associated are more. A cascade control structure consists of two control loops, a secondary intermediate loop and a primary outer loop. The idea of cascade structure is that the disturbances introduced in the inner loop are reduced to a greater extent in the inner loop itself before they extend into the outer loop.

Kaya (2001) proposed a cascade control scheme combined with a Smith predictor for stable cascade processes with dominant time delay and achieved better control performance. The design and analysis of cascade control strategies for stable processes are addressed by many researchers (Huang *et al*., 1998; Rao *et al*., 2012; Lee *et al*., 1998). However, limited research has been carried out for the design of cascade control strategies for unstable processes. The control of open-loop unstable processes are much more difficult than the control of stable processes. Existence of unstable systems is well described by Sree and Chidambaram (2006). Many IMC based cascade control scheme for unstable processes with four controllers were proposed (Liu *et al*., 2005; Kaya *et al*., 2006) proposed a cascade control structure for controlling unstable and integrating processes with four controllers. Uma *et al*., (2009) proposed an improved cascade control scheme for unstable processes using a modified Smith predictor with three controllers and one filter in the outer feedback path. In the work of Kaya and Atherton (2006) and Liu *et al*., (2005) one of the controllers is used only for stabilization and in Uma *et al*., (2009) scheme there is one filter in the feedback path to improve the performance of the unstable processes. Recently, Santhosh and Chidambaram (2013) proposed a simple method based on equating the coefficients of corresponding powers of s and s^2 in the numerator to α_1 and α_2 times those of the denominator of the closed-loop transfer function for a servo problem and used two tuning parameters. In the proposed structure, there is no special controller for stabilization, rather the closed-loop controllers are used for rejecting the load disturbances as well as for stabilizing the unstable processes. Most of the methods discussed above involve many controllers with complex design methods and fail with respect to robustness issues in case of uncertainty in process parameters. In practice, a

*Corresponding author: Dr. M. Chidambaram
e-mail: chidam@iitm.ac.in

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simple and robust controller structure is desirable. This paper shows how to overcome the above deficiencies using a new cascade control structure in which secondary controller is an IMC controller and the primary controller is H2 minimization based PID controller. Disturbance rejection in process industries is commonly much more important than set point tracking for any process control applications. This is because set point changes are often only made when the production rate is altered. The proposed scheme leads to substantial control performance improvement for the disturbance rejection also. Tuning rules are derived for the controllers used in the proposed structure for effective control of open-loop unstable plants. Robustness and performance of the proposed method have been analyzed. Simulation examples are provided to show how the proposed design method is superior to the method used by Lee *et al*., (2002) where two PID controllers along with filters were used.. For clear interpretation, the paper is organized as follows. Section 2 describes the proposed cascade control structure and controller design methods are discussed. In Section 3, the simulation results were displayed satisfying the performance and robustness issues in case of uncertainty in process parameters also and the selection of tuning parameters is given followed by the conclusions at the end.

2. PROPOSED METHOD

A new cascade control structure is proposed for open-loop unstable processes as shown in Fig. 1 where a PID controller in series with a lead-lag compensator is incorporated in the outer loop. G_{p1}, G_{p2} are the outer and the inner loop processes. θ_1 and θ_2 are the time delays of G_{p1} and G_{p2}, respectively. G_{m2} is the secondary process model. Gc_2 is the secondary loop controller. The overall process transfer function for the outer loop is $G_p = G_{p2}\, G_{p1}\, G_{c2}$.

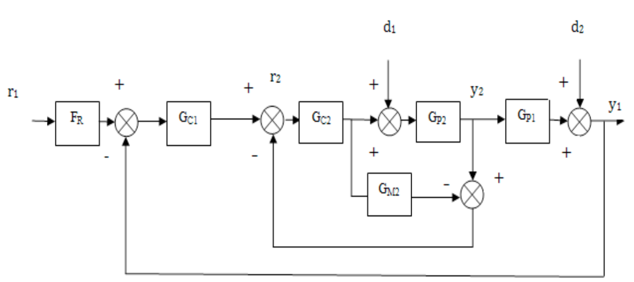

Fig. 1. Cascade Process with IMC and H2 optimal PID controller along with a filter.

Both processes considered here are of first order. The secondary process is considered to be stable or integrating whereas primary process is always unstable. So the control of secondary process is simple as compared to primary process. The action should be taken to stabilize the system as well as for disturbance rejection. Better performance can be obtained by approximating the controller expression as a PID controller using Maclaurin series expansion. This is proved to be a good approximation by Lee et al. (1998).

2.1 Design of Secondary loop Controller

G_{c2} is an IMC controller in the secondary loop which stabilizes the process by rejecting the disturbance entering in the secondary loop. The closed loop transfer function of the secondary loop is given by

$$\frac{y_2}{r_2} = \frac{G_{c2}\, G_{p2}}{(1-G_{c2}\, G_{m2} + G_{c2}\, G_{m2})} \tag{1}$$

Here the transfer function of the secondary process is considered with a stable pole and is given as

$$G_{p2} = \frac{K_{p2}\, e^{-\theta p2s}}{(\tau_{p2}s+1)} \tag{2}$$

G_{m2} is the model of the secondary process and is given as

$$G_{m2} = \frac{K_{m2}\, e^{-\theta m2s}}{(\tau_{m2}s+1)} \tag{3}$$

As per the IMC strategy used by Uma et al., (2009), the controller transfer function is considered as

$$G_{c2} = \frac{\tau_{m2}s+1}{K_{m2}\,(\lambda_2 s+1)} \tag{4}$$

This IMC structure is the desirable one to get the improved performance. Here λ_2 is the tuning parameter. Selection of λ_2 is done such that it rejects the disturbance entering the inner loop faster and gives a stabilized output.

2.2 Design of Primary loop Controller

The primary loop controller is designed using IMC based PID controller design using H_2 minimization (Nasution *et al*., 2011). Here overall process is considered as $G_p = y_2/r_2 *G_{p1}$ where G_p is considered as a second order unstable process and G_m is the process model and is given as

$$G_p = \frac{K\, e^{-\theta s}}{(\tau_1 s-1)(\tau_2 s-1)} \tag{5}$$

$$G_m = \frac{K\, e^{-\theta ms}}{(\tau_1 s-1)(\tau_2 s-1)} \tag{6}$$

where $\theta_m = \theta_{m1} + \theta_{m2}$, $\tau_2 = -\lambda_2$, $K = -K_{p1}$.

The equivalent controller in a conventional feedback form can be written as $G_c = G_{imc}/(1 - G_{imc}\, G_m)$. According to H_2 optimal controller design (Morari and Zafiriou, 1989), the IMC controller along with filter F(s) is designed as given, $G_{imc}(s) = \tilde{G}_{imc}(s)F(s)$ to make the $G_{imc}(s)$, a realizable controller and also to maintain robustness. $G_{imc}(s)$ is designed to achieve H_2 optimal performance for a specific input type, ν(s). The process model and the input are divided into minimum phase part and non-minimum phase part as $G_m(s) = G_-(s)G_+(s)$ and $v(s) = v_-(s)v_+(s)$ where " – " refers to the minimum phase part and " + " refers to non minimum phase part. Further, the Blachke product of RHP poles of $G_m(s)$ and $\nu(s)$ are introduced as

$$b_m(s) = \prod_{i=1}^{k} (-s + p_{mi}) / (s + \bar{p}_{mi}) \tag{7a}$$

$$b_v(s) = \prod_{i=1}^{k} (-s + p_{vi}) / (s + \bar{p}_{vi}) \tag{7b}$$

where p and $\bar{p}$ are the RHP pole and its conjugate. Then the H_2 optimal controller is derived using

$$\tilde{G}_{imc}(s) = b_p (\tilde{G}_{m-} b_v v_-)^{-1} \{ (b_p \tilde{G}_{m+})^{-1} b_v v_- \}_* \tag{8}$$

where $\{...\}_*$ is defined as the operator obtained after omitting all terms involving the poles of $(G_{m+})^{-1}$ after taking partial fraction expansion. In the present work, for the overall unstable process (5), the required quantities for the operator are obtained as

$$\tilde{G}_{m-}(s) = \frac{k}{\tau_1\tau_2\left(-s+\frac{1}{\tau_1}\right)\left(-s+\frac{1}{\tau_2}\right)}; \tilde{G}_{m+}(s) = e^{-\theta s}$$

$$v_-(s) = \frac{k}{\tau_1\tau_2\left(-s+\frac{1}{\tau_1}\right)\left(-s+\frac{1}{\tau_2}\right)s}; v_+(s) = 1$$

$$b_p(s) = \left(-s+\frac{1}{\tau_1}\right)\left(-s+\frac{1}{\tau_2}\right) \Big/ \left(s+\frac{1}{\tau_1}\right)\left(s+\frac{1}{\tau_2}\right)$$

$$b_p(s) = \left(-s+\frac{1}{\tau_1}\right)\left(-s+\frac{1}{\tau_2}\right) \Big/ \left(s+\frac{1}{\tau_1}\right)\left(s+\frac{1}{\tau_2}\right) \tag{9}$$

Substituting these values in (7) IMC controller is obtained (Anusha *et al.*, 2012) as

$$\tilde{G}_{imc} = \frac{(\tau_1 s-1)(\tau_2 s-1)}{k}\left[\frac{\tau_1\tau_2(\tau_1-\tau_2-\tau_1 e^{\theta/\tau_1}+\tau_2 e^{\theta/\tau_2})s^2+(\tau_1^2 e^{\theta/\tau_1}-\tau_2^2 e^{\theta/\tau_2}+\tau_2^2-\tau_1^2)s+(\tau_1-\tau_2)}{(\tau_1-\tau_2)}\right] \tag{10}$$

Considering the filter as $F(s) = \alpha_2 s^2+\alpha_1 s+1)/(\lambda s+1)^4$, the IMC controller is obtained as Then the equivalent controller in a conventional feedback form is obtained from IMC structure as $G_c = G_{imc} / (1 - G_{imc} G_m)$. After substituting G_{imc} and G_m, G_c will be obtained as a higher order numerator and denominator expression. To simplify this expression to a PID controller form, Maclaurin series is used here. To do that, let us define $J(s) = s\, G_c(s)$. Expand $J(s)$ using Maclaurin series expansion to obtain the controller $G_c(s)$ as

$$G_c(s) = \frac{1}{s}\left(J(0) + J'(0)s + \frac{J''(0)}{2!}s^2 + \cdots\right) \tag{11}$$

By considering this as a PID controller in the form given as

$$G_c(s) = k_c\left(1 + \frac{1}{\tau_i}s + \tau_d s\right) \tag{12}$$

the PID controller parameters are obtained as shown below

$$k_c = J'(0), \qquad \tau_i = \frac{J'(0)}{J(0)} \quad and \quad \tau_d = \frac{J''(0)}{2J'(0)} \tag{13}$$

where

$$J(0) = 1/p_m(0)D(0)$$

$$J'(0) = -[p_m'(0)D(0) + p_m(0)D'(0)]/[p_m(0)D(0)]^2$$

$$J''(0) = J'(0)\left[\frac{p_m''(0)D(0) + 2p_m'(0)D'(0) + p_m(0)D''(0)}{p_m'(0)D(0) + p_m(0)D'(0)} + \frac{2J'(0)}{J(0)}\right]$$

$$D(0) = 4\lambda - p_A'(0); D'(0) = [12\lambda^2 - p_A''(0)]/2; D''(0) = [24\lambda^3 - p_A'''(0)]/3$$

$$p_A'(0) = \frac{(\tau_1-\tau_2)(-\theta+\alpha_1)+\tau_1 b-\tau_2 a}{\tau_1-\tau_2}$$

$$p_A''(0) = \frac{(\tau_1-\tau_2)(\theta^2-2\alpha_1\theta+2\alpha_2)+2(\tau_1 b-\tau_2 a)(-\theta+\alpha_1)+2\tau_1\tau_2(a-b)}{\tau_1-\tau_2}$$

$$p_A'''(0) = \frac{(\tau_1-\tau_2)(-\theta^3+3\alpha_1\theta^2-6\alpha_2\theta)+(\tau_1 b-\tau_2 a)(3\theta^2-6\alpha_1\theta+6\alpha_2)+2\tau_1\tau_2(a-b)(-3\theta+3\alpha_1)}{\tau_1-\tau_2}$$

$$p_m(0) = k; p_m'(0) = \frac{-k\left((\tau_1-\tau_2)(-\tau_2-\tau_1+\alpha_1)+\tau_1 b-\tau_2 a\right)}{(\tau_1-\tau_2)}$$

$$p_m''(0) = \frac{\begin{array}{l}-k[(\tau_1-\tau_2)2(\tau_1-\tau_2)(\tau_1\tau_2-\alpha_1\tau_2-\alpha_1\tau_1+\alpha_2)+2(\tau_1 b-\tau_2 a)(-\tau_2-\tau_1+\alpha_1)+2\tau_1\tau_2(a-b)- \\ 2\left((\tau_1-\tau_2)(-\tau_2-\tau_1+\alpha_1)+\tau_1 b-\tau_2 a\right)^2]\end{array}}{(\tau_1-\tau_2)^2}$$

In which α_1 and α_2 values are obtained from the requirements to satisfy internal stability in IMC based control schemes. The condition for internal stability is

$$(1 - G_{imc}G_m)\big|_{s=\frac{1}{\tau_1},\frac{1}{\tau_2}} = 0$$

Thus

$$\alpha_1 = \left(\frac{\lambda}{\tau_1}+1\right)^4 \frac{\tau_1^2 e^{\theta/\tau_1}}{x} - \left(\frac{\lambda}{\tau_2}+1\right)^4 \frac{\tau_2^2 e^{\theta/\tau_1}}{y} - \tau_1^2 + \tau_2^2$$

$$\alpha_2 = \left(\frac{\lambda}{\tau_1}+1\right)^4 \frac{(\tau_1-\tau_2)}{x}\tau_1^2 e^{\theta/\tau_1} - \tau_1^2 - \alpha_1\tau_1$$

$$x = \frac{\tau_2}{\tau_1}(a-b) + \frac{(\tau_1 b - \tau_2 a)}{\tau_1} + \tau_1 - \tau_2$$

$$y = \frac{\tau_1}{\tau_2}(a-b) + \frac{(\tau_1 b - \tau_2 a)}{\tau_2} + \tau_1 - \tau_2$$

$$a = \tau_2(e^{(\theta/\tau_2)} - 1); b = \tau_1(e^{(\theta/\tau_1)} - 1) \tag{14}$$

3. SIMULATION RESULTS

To analyze the performance of the proposed design method, three examples are considered.

3.1 Example-1: Consider the cascade process as shown below

$$G_{p1} = \frac{e^{-4s}}{20s-1}; \qquad G_{p2} = \frac{2e^{-2s}}{20s+1} \tag{15}$$

The tuning parameter λ_2 is selected in the range of Θ_{m2} to 1.5 Θ_{m2}. Here λ_2 chosen as 2.5. To select the tuning parameter (λ), an analysis is carried out here based on Maximum

Sensitivity, Ms. Fig. 2. shows the variation of Maximum Sensitivity (Ms) with respect to the tuning parameter, λ.

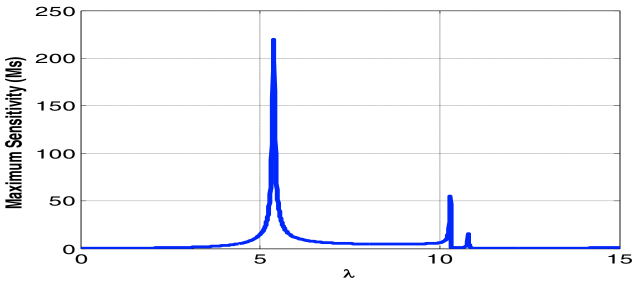

Fig. 2. Maximum Sensitivity versus λ_2 for Example 1

There exist a large value for Ms corresponding to λ = 5.5 after which the Ms decreases up to λ = 9 and then Ms increases. Hence λ should be selected in the range of 6 – 8.5. Within this range of λ, the maximum value for Ms will be 4.75. If λ is selected outside this range the closed loop performance is not good or is not stable. Note that the minimum value of Ms achievable in this range of λ is 7. It can be observed from the figure that one should not select λ without proper analysis. Here the controller settings obtained are k_c = 3.5411, τ_i = 39.3247, τ_d = 4.8137 and the set weight chosen is 0.3. This is compared with Lee et al. (2002) where two PID controllers have been used, one for secondary k_{cs} = 6.92, τ_{is} = 4.6, τ_{ds} = 0.79 and other for primary loop k_{cp} = 3.31, τ_{ip} = 36.22, τ_{dp} = 3.08 along with two filters α = 3.66, β =32.91. With these controller settings the methods are simulated by giving a unit step change in set point. Fig. 3 and Fig. 4 shows the closed loop servo and regulatory responses where the proposed method is superior to the method suggested by Lee et.al. (2002).

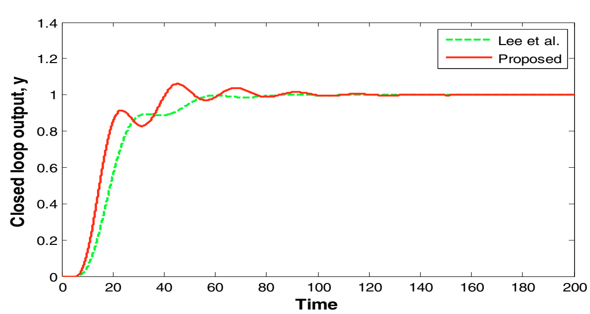

Fig. 3. Closed-loop responses due to a set point change.

Table 1. Performance Comparison for Example 1

Uncertainty in process parameters	Criteria	Proposed Method		Lee et al. Method	
		Servo	Load Change	Servo	Load Change
0%	IAE	18.46	197.79	22.03	197.81
	ISE	12.96	196.49	16.31	196.86
	ITAE	277.57	*	317.63	*
40% decrease in K_{p2}	IAE	18.46	202.21	30.50	201.98
	ISE	12.96	205.33	17.56	207.07
	ITAE	277.57	*	1238.8	*
20% increase in Θ_{p1} & 30% decrease in Θ_{p2}	IAE	19.03	197.79	24.61	197.83
	ISE	13.13	196.56	17.00	197.66
	ITAE	325.41	*	564.45	*
10% increase in τ_{p1} & 20% decrease in τ_{p2}	IAE	18.47	202.21	26.66	202.24
	ISE	13.37	205.29	17.18	206.93
	ITAE	248.87	*	1044.2	*

Table 1. shows the performance criterias with respect to Integral absolute error (IAE), Integral square error (ISE) and Integral time weighted absolute error (ITAE), for servo and regulatory responses under perfect and uncertainty in process parameter conditions.In which Table1 * indicates unstable behaviour.

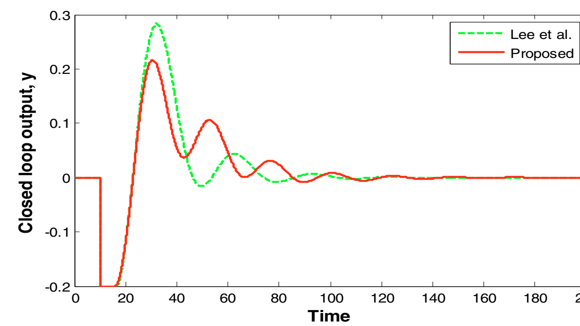

Fig. 4. Closed-loop responses for a load change in primary loop for Example 1

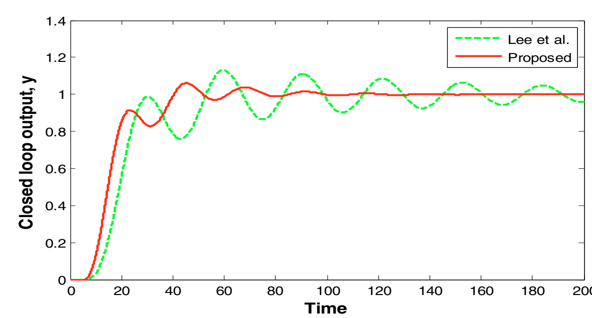

Fig. 5. Closed-loop responses due to a set point for 40% decrease in K_{p2}.

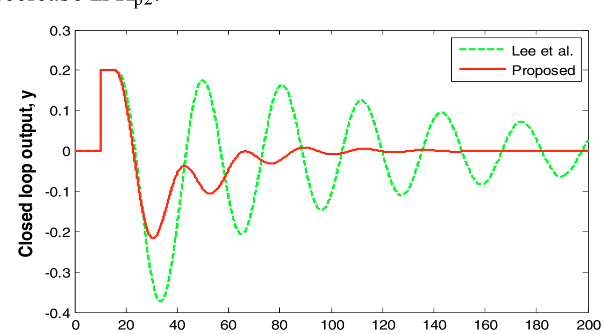

Fig. 6. Closed-loop responses due to a load change in primary loop for 40% decrease in K_{p2}.

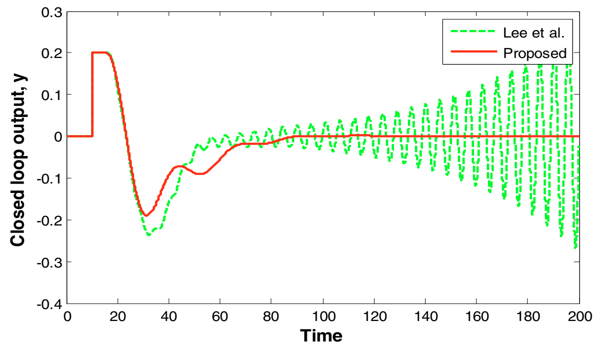

Fig. 7. Closed-loop responses due to a load change in primary loop for 10% increase in τ_{p1} & 20% decrease in τ_{p2}.

The proposed controller is evaluated in terms of robustness for uncertainty (increase or decrease) in the process gain, time constants and the time delay in the inner loop as well as in the outer loop (e.g., for simulation the gain is increased by 1.1 times the original value used in the design of the controller). Figs. 5–7 show the servo and regulatory responses for uncertainties in different parameters like inner and outer loop process gains, inner and outer loop time constants, inner and outer loop time delays. For each of the cases, a better robust performance is obtained for the proposed method when parameters are perturbed.

3.2 Example-2: Consider the cascade process as shown below

$$G_{p1} = \frac{e^{-4s}}{20s-1}; \qquad G_{p2} = \frac{2e^{-2s}}{s} \tag{16}$$

The tuning parameter λ_2 is chosen as 3. The tuning parameter λ is found out through an analysis based on maximum sensitivity and is chosen as 8.8. Here the controller settings obtained are $k_c = 2.9586$, $\tau_i = 51.8802$, $\tau_d = 5.0928$ and set weight is chosen as 0.3. On comparison with Lee et al. (2002) whose inner loop parameters are $k_{cs} = 0.35$, $\tau_{is} = 5.02$, $\tau_{ds} = 0.82$ and outer loop PID controller is $k_{cp} = 3.31$, $\tau_{ip} = 36.22$, $\tau_{dp} = 3.08$ with $\alpha = 4.07$, $\beta = 32.91$, the simulation results were obtained and the proposed method is found to be superior.

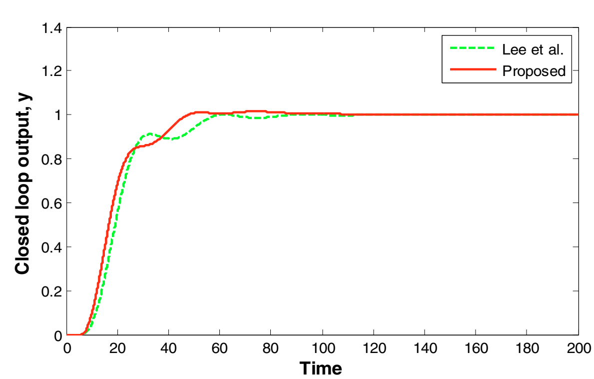

Fig. 8. Closed-loop responses due to a set point change for Example 2.

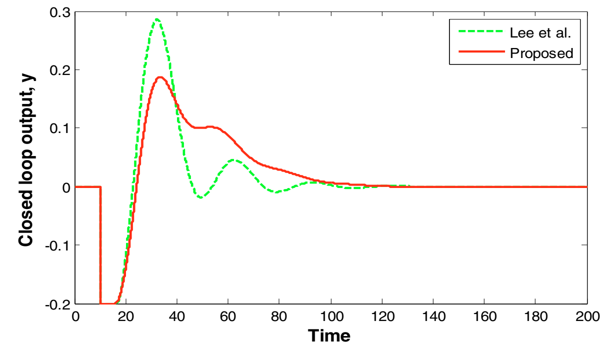

Fig. 9. Closed-loop responses for a load change in primary loop.

The IAE, ISE and ITAE performance comparison are given in Tables 2. The servo and regulatory responses are shown in Figs. 8 and 9. From the figures, we can see that the proposed method gives a better performance than the previously reported method. The response stabilises faster when compared to the equating coefficient method. For robustness studies, outer loop and inner loop parameters are varied, i.e., process gain, time constant and time delay. It is found that when the parameters are varied the proposed method maintains its stability for set point change and the load change. The performance of the proposed method is much better as seen in Table 2 and from Figs. 10 – 12, when there is an uncertainty in process parameters than the method suggested by Lee et al. (2002).

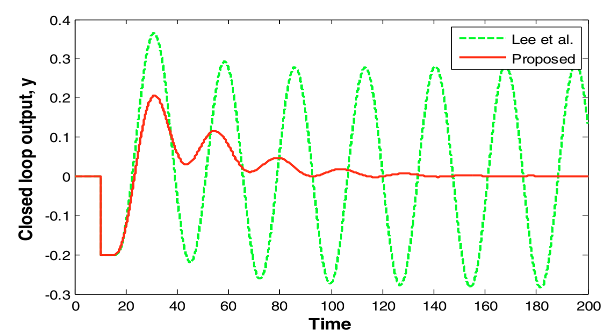

Fig. 10. Closed-loop responses due to a load change for 20% increase in K_{p1} & 20% decrease in K_{p2}.

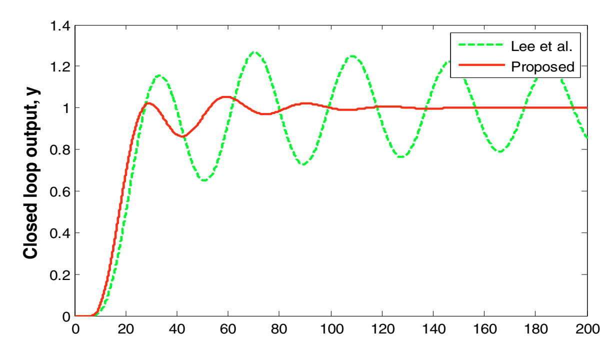

Fig. 11. Closed-loop responses due to a set point change for 40% increase in Θ_{p1} & 20% decrease in Θ_{p2}.

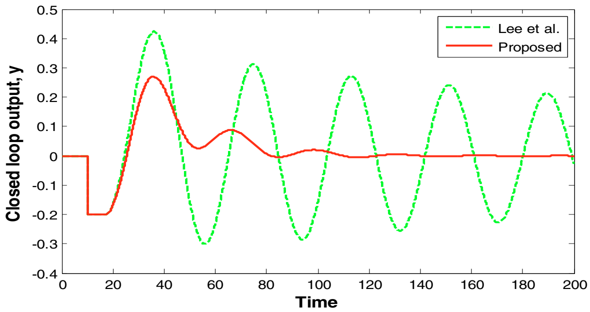

Fig. 12. Closed-loop responses due to a load change for 40% increase in Θ_{p1} & 20% decrease in Θ_{p2}.

Table 2. Performance Comparison for Example 2

Uncertainty in process parameters	Criteria	Proposed Method		Lee et al. Method	
		Servo	Load Change	Servo	Load Change
0%	IAE	19.98	196.49	22.04	197.81
	ISE	14.43	194.03	16.31	196.85
	ITAE	280.89	*	318.20	*
20% increase in K_{p1} & 20% decrease in K_{p2}	IAE	21.93	197.08	43.00	198.46
	ISE	14.21	195.09	19.84	204.94
	ITAE	408.88	*	*	*
40% increase in Θ_{p1} & 20% decrease in Θ_{p2}	IAE	20.65	196.50	46.25	198.03
	ISE	15.21	194.40	22.40	204.07
	ITAE	343.13	*	*	*
10% decrease in τ_{p1} & 10 % increase in τ_{p2}	IAE	19.38	196.50	23.95	197.79
	ISE	13.86	194.07	15.97	197.37
	ITAE	267.88	*	524.17	*

4. CONCLUSIONS

A novel method of designing PID controllers for open loop unstable cascade systems is proposed. This method is based on IMC based H2 minimization concept where Maclaurin series is used to approximate the controller expression as a PID controller. The servo and regulatory responses are found to be much better when compared to that of the method suggested by Lee et al. An advantage is that only two tuning parameters are required for this method. Robustness issues are considered using maximum sensitivity graphs. From the two simulation examples, the simplicity and effectiveness of the proposed method seems superior than the method reported and the responses under perfect as well perturbed conditions seems satisfactory.

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