RESEARCH NOTES

Two-Step IMC−PID Method for Multiloop Control System Design

Sungyoup Cha, Daewoong Chun, and Jietae Lee*

Department of Chemical Engineering, Kyungpook National University, Taegu 702-701, Korea

Proportional−integral−derivative (PID) controller tuning method based on the internal model control is one of the simplest tuning rules and provides excellent performances for various processes. It has one design parameter which determines the speed of closed-loop response. As the design parameter changes, the controller gain changes while integral and derivative times usually remain constant. Hence, the method can be extended easily to the design of multiloop control systems because there are simple methods to find stable multiloop proportional controller gains. However, integral and derivative times independent of the design parameter can cause poor closed-loop responses for some processes such as those with small dead times. For such processes, 2 degree of freedom control systems are usually required, and a two-step method where a proportional controller is designed first and then a PID controller is designed for the compensated system can be used to design the 2 degree of freedom control systems. This two-step method is applied to the design of multiloop control systems for interacting multivariable processes.

Downloaded by CHINESE ACAD SCI CAOS CONSORT on June 29, 2009
Published on May 17, 2002 on http://pubs.acs.org | doi: 10.1021/ie0102347

1. Introduction

The internal model control (IMC) method[1] can be used to design proportional−integral−derivative (PID) controllers for single-input single-output (SISO) processes. The IMC−PID method is very simple and provides excellent PID controllers for various processes. It has one design parameter of the closed-loop time constant. As the design parameter changes, only the proportional gain changes while integral and derivative times are usually independent of it. When this fact of the IMC−PID method is utilized, the method can be applied to the design of multiloop control systems.[2,3] However, it can be a demerit to hinder the obtainment of control performances for some processes. For example, the IMC−PID method provides control systems with poor load responses for some processes such as those having small time delays.[1] For such processes, large integral times compared with the closed-loop time constants result and load responses can be poor. To resolve this disadvantage, we may use a two-step method where a proportional (P) controller is designed first and then the IMC−PID method is applied to the process compensated by the P controller.[4] This two-step method can also be applied to unstable processes stabilizable by a P controller. The resulting control system becomes a kind of 2 degree of freedom (2DOF) control system.

Multiloop control systems can be designed by the SISO IMC−PID method. The IMC−PID method is applied to diagonal transfer functions, ignoring interactions, and then the design parameters of the IMC−PID method are adjusted to compensate for interactions. Because design parameters of the IMC−PID method affect only the proportional gains, they can be easily determined by methods such as the Nyquist array method. As in the SISO case, this multiloop IMC−PID method can be poor for some processes. Here, the above two-step method is tried to enhance the multiloop IMC−PID method.

Several methods for the 2DOF control system such as the set-point weight on the proportional gain[5] are available and are still being investigated. However, their feedback parts in the 2DOF control systems are not straightforward to the design for multiloop systems. They are not considered here because our primary object of this study is to design feedback parts of multiloop control systems via the IMC−PID method. The proposed design method is compared with the well-known biggest log-modulus tuning (BLT) method[6] and the sequential autotuning (SAT) method.[7,8] The proposed method can handle unstable processes stabilizable by P controllers.

2. Two-Step IMC−PID Method for SISO Processes

For a process with small time delay compared to time constant, the design parameter of the closed-loop time constant in the IMC−PID method can be chosen to be very small, resulting in fast set-point responses. However, responses for load changes in the input can be sluggish because of slow open-loop dynamics.[1] For example, consider a process $G(s) = 1/(s + 1)$. The IMC−PI controller becomes $C(s) = (1 + 1/s)/\lambda$. While the closed-loop transfer function for the set-point change is $1/(\lambda s + 1)$, that for the load change in the input becomes $\lambda s/(\lambda s + 1)/(s + 1)$. With a decrease in λ, the set-point response can be made to be very fast. However, because

* Corresponding author. Tel: +82-53-950-5620. Fax: +82-53-950-6615. E-mail: jtlee@knu.ac.kr.

10.1021/ie0102347 CCC: $22.00 © 2002 American Chemical Society
Published on Web 05/17/2002

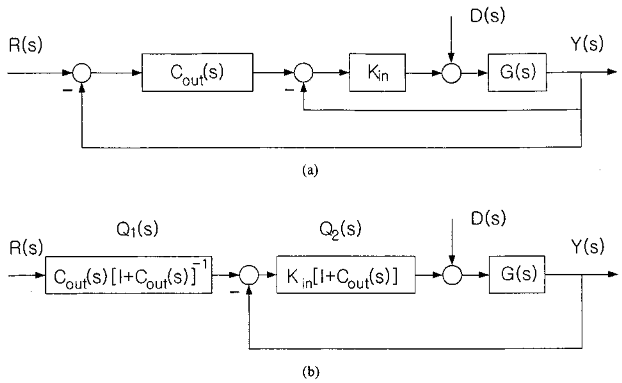

Figure 1. Proposed control system (a) and its equivalent 2DOF control system (b).

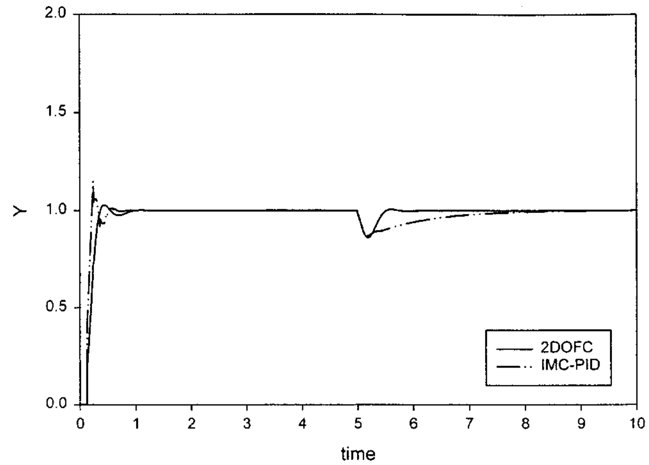

Figure 2. Step set-point and load responses for the process $G(s) = \exp(-0.1s)/(s + 1)$ ($\lambda = 0.05$ and a load change occurs at the process input).

of the pole at -1, the load response cannot be made to be fast. The large integral time compared with the closed-loop time constant λ indicates the problem. It may be cured by using other controller tuning methods such as the pole placement method.[5] However, simplicity of the IMC method may not be maintained, and extension to multiloop control systems is not straightforward. For such processes, basically the 2DOF control system should be used to obtain good control performances for both set-point and load changes.[9] Unstable processes including integrating processes also require 2DOF control systems for better set-point and load responses. For a method applicable to multiloop control systems, the two-step IMC−PID method where a P controller is designed first and then the IMC−PID method is applied to the compensated process is investigated here.

The two-step method shown in Figure 1 can be used to design 2DOF control systems. An inner P controller is designed first. Then the outer controller is designed by the IMC method.[1] The characteristic equation becomes

$$Z(s) = 1 + K_{in}G(s) + K_{in}C_{out}(s)\, G(s)$$

The outer controller is designed by specifying $F(s) = K_{in}C_{out}(s)\, G(s)/[1 + K_{in}G(s)]$.[1] Hence, we have

$$Z(s) = [1 + F(s)][1 + K_{in}G(s)]$$

and the closed-loop poles of the control system of Figure 1 include zeros of $1 + K_{in}G(s) = 0$. They become open-loop poles of $G(s)$ as K_{in} goes to zero (the standard IMC method). These open-loop poles of $G(s)$ can cause slower load responses of the closed-loop system. With introduction of K_{in}, these poles can be moved, resulting in the control system with faster load responses.

A practical method for K_{in} and $C_{out}(s)$ is now described. For stable processes and some integrating processes, the gain of the inner P controller can be designed by the Ziegler−Nichols method as

$$K_{in} = K_u/4 \tag{1}$$

where K_u is the ultimate gain of the process $G(s)$.[4] For some unstable processes, De Paor and O'Malley[10] also proposed stable controller gains.

For the outer controller, the IMC−PID method is used with approximation of the closed-loop system by a second-order plus time delay (SOPTD) model

$$\bar{G}(s) = \frac{G(s)}{1 + K_{in}G(s)} \approx \frac{k_{cl}\exp(-\theta_{cl}s)}{\tau_{cl}^2 s^2 + 2\zeta_{cl}\tau_{cl}s + 1} \tag{2}$$

where $\bar{G}(s)$ represents the transfer function of a closed-loop system compensated by the inner P controller. Parameters of the approximate SOPTD model can be obtained by fitting $\bar{G}(s)$ in the frequency domain. The fitting criterion is

$$J = \sum_{\omega=\Omega}\left\|\bar{G}(j\omega) - \frac{k_{cl}\exp(-j\theta_{cl}\omega)}{\tau_{cl}^2(j\omega)^2 + 2\zeta_{cl}\tau_{cl}(j\omega) + 1}\right\| \tag{3}$$

where Ω is a set of frequency points. To minimize the above criterion, the Newton−Raphson method is used. The method in work by Park et al.[11] requiring simpler computations can also be used to obtain the approximate SOPTD model from frequency response information.

The control system of Figure 1a can be rearranged as the control system of Figure 1b

$$Q_1(s) = C_{out}(s)/[1 + C_{out}(s)] \tag{4}$$

$$Q_2(s) = K_{in} + C_{out}(s) \tag{5}$$

If $C_{out}(s)$ is PID, $Q_1(s)$ becomes a kind of lead/lag module

$$Q_1(s) = (\alpha_1 s^2 + \alpha_2 s + 1)/(\beta_1 s^2 + \beta_2 s + 1) \tag{6}$$

and $Q_2(s)$ becomes PID.

$$Q_2(s) = k_c(1 + 1/\tau_I s + \tau_D s) \tag{7}$$

Figure 2 shows responses of the proposed control system and the IMC−PID control system for the process $G(s) = \exp(-0.1s)/(s + 1)$. The design parameter λ is set to 0.05. As shown above, the IMC−PID controller shows a very sluggish response for the step load change in the input. On the other hand, the sluggish load response disappeared in the proposed 2DOF control system.

3. Multiloop Control System Design

The IMC method can be applied to the design of a multiloop control system.[2,3] Controllers in the multiloop

Downloaded by CHINESE ACAD SCI CAOS CONSORT on June 29, 2009
Published on May 17, 2002 on http://pubs.acs.org | doi: 10.1021/ie0102347

Downloaded by CHINESE ACAD SCI CAOS CONSORT on June 29, 2009
Published on May 17, 2002 on http://pubs.acs.org | doi: 10.1021/ie0102347

Table 1. Multiloop PI Control Systems for the WB Column

	BLT method	SAT method	IMC method	ICC method
K	0.375	0.868	0.737	0.850
	−0.075	−0.0868	−0.103	−0.0885
τ_I	8.29	3.246	17.2	7.21
	23.6	10.4	15.9	8.86

control system are designed for the paired transfer functions, ignoring interactions, and then the design parameters of the IMC method are adjusted to ensure stability robustness under interactions. It is very simple to determine the design parameters because they affect only the proportional gains. The Nyquist array method[12,13] or a more elaborate method guaranteeing robust performances[2] can be used. This method is as simple as some other methods such as the BLT method[6] and the sequential loop closing method.[7] However, integral and derivative times which are the same as those of control systems for the paired transfer functions may not be desirable for some multivariable processes, resulting in poor control performances.

Poor control performances are indicated by large integral times in multiloop PI control systems. Large integral times appear in many design methods such as the BLT method and the SAT method,[7] including the multiloop IMC−PI method.[3] Consider the Wood and Berry column[6] in the example section. Control systems designed by BLT, SAT, multiloop IMC−PI, and iterative continuous cycling (ICC) methods[13] are shown in Table 1. The BLT, SAT, and IMC−PI methods provide larger integral times for the second loop than the ICC method, and sluggish responses result.[13]

To resolve problems of the IMC−PID method for multiloop control systems while maintaining the simplicity of the IMC−PID method, the two-step method in the previous section is applied. The design procedure is as follows.

Step 1. Applying the Nyquist array method of Lee et al.[13] to the process $G(s)$, obtain the largest stable gain obtainable and set the inner P controller gain to one-fourth.

Step 2. Calculate the frequency response of $\bar{G}(s) = G(s)\,[I + K_{in}G(s)]^{-1}$ and obtain approximate SOPTD models of its diagonal elements by fitting their frequency responses.

Step 3. Applying the IMC−PID method[1] to the approximate SOPTD models of step 2, obtain integral times and derivative times of $C_{out}(s)$.

Step 4. Applying the Nyquist array method to the compensated process of $\bar{G}(s)\,C_{out}(s)$, obtain the largest stable gain and set the outer controller gain to 1/3.3.

4. Examples

The proposed 2DOF control method is compared with other well-known methods of the BLT and SAT methods. A 1 degree of freedom (1DOFC) controller with $Q_1(s) = I$ is also considered for fair comparisons.

Stable Processes. Methods to design multiloop control systems are applied to the following three 2 × 2

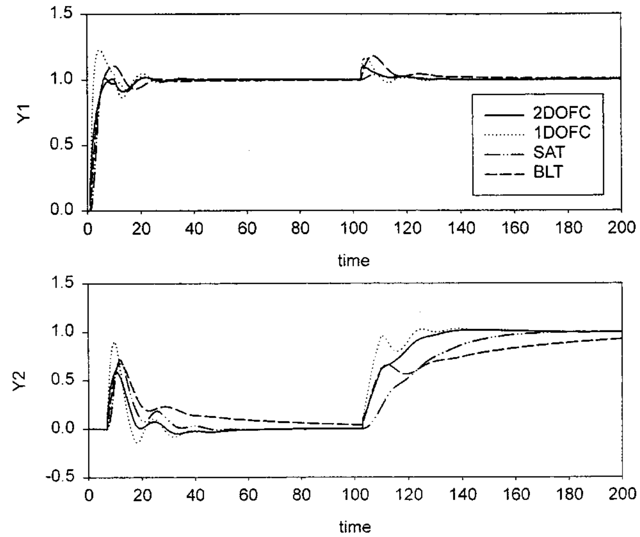

Figure 3. Step set-point responses for the WB column.

processes and one 3 × 3 process shown in work by Luyben.[6]

Wood and Berry (WB) column:

$$G(s) = \begin{bmatrix} \dfrac{12.8\exp(-s)}{16.7s+1} & \dfrac{-18.9\exp(-3s)}{21s+1} \\ \dfrac{6.6\exp(-7s)}{10.9s+1} & \dfrac{-19.4\exp(-3s)}{14.4s+1} \end{bmatrix}$$

Wardle and Wood (WW) column:

$$G(s) = \begin{bmatrix} \dfrac{0.126\exp(-6s)}{60s+1} & \dfrac{-0.101\exp(-12s)}{(48s+1)(45s+1)} \\ \dfrac{0.094\exp(-8s)}{38s+1} & \dfrac{-0.12\exp(-8s)}{35s+1} \end{bmatrix}$$

Ogunnaike and Ray (OR) column:

$$G(s) = \begin{bmatrix} \dfrac{0.66\exp(-2.6s)}{6.7s+1} & \dfrac{-0.61\exp(-3.5s)}{8.64s+1} & \dfrac{-0.0049\exp(-s)}{9.06s+1} \\ \dfrac{1.11\exp(-6.5s)}{3.25s+1} & \dfrac{-2.36\exp(-3s)}{5s+1} & \dfrac{-0.01\exp(-1.2s)}{7.09s+1} \\ \dfrac{-34.68\exp(-9.2s)}{8.15s+1} & \dfrac{46.2\exp(-9.4s)}{10.9s+1} & \dfrac{0.87(11.61s+1)\exp(-s)}{(3.89s+1)(18.8s+1)} \end{bmatrix}$$

Table 2 shows the inner P controller gains and the approximate SOPTD model parameters. Table 3 shows the outer controller $C_{out}(s)$.

Figures 3−5 show the set-point responses for the WB, WW, and OR columns. For all processes, the BLT method shows slower set-point responses in some loops. The BLT method uses the detuning strategy, and poor responses are due to the large detuning to obtain the stability robustness. This disadvantage of the BLT method may be resolved by using different detuning strategies based on a more elaborate stability criterion for multivariable systems, but simplicity is not maintained.

For the WB and WW columns, the SAT method also shows slower set-point responses in some loops. The SAT method tunes the multiloop control system sequentially. Hence, later loops may be tuned loosely, and their set-point responses will be sluggish.

The proposed 2DOF control systems remove these sluggish responses throughout the above example pro-

Table 2. Inner P Controllers, Approximate Models, and Outer PID Controllers

process	frequency range (Ω)	K_{in}	approximate model[a]	outer controller[b] [$C_{out}(s)$]
WB	0.0001−1.6003	0.3934	(0.7915, 1.1528, 0.9010, 0.6074)	(0.9754, 2.0774, 0.6397)
	0.0001−0.4872	−0.0588	(0.3929, 2.2422, 0.6428, 2.6436)	(0.7186, 2.8824, 1.7442)
WW	0.0001−0.2725	29.02	(0.7074, 5.8485, 0.7018, 4.0273)	(0.9461, 8.2085, 4.1670)
	0.0001−0.2095	−12.43	(0.4645, 7.6292, 0.5148, 4.7615)	(0.9036, 7.8549, 7.4100)
OR	0.0001−0.6748	0.826	(0.2908, 2.5842, 0.5642, 1.3546)	(0.8946, 2.9162, 2.2900)
	0.0001−0.5873	−0.1664	(0.2345, 2.5292, 0.5096, 1.6409)	(0.9290, 2.5776, 2.4818)
UB	0.0001−1.6638	1.631	(0.5414, 0.4625, 2.1912, 0.9518)	(0.5666, 2.0267, 0.1055)
	0.0001−100	2	(1.1937, 0.0836)[c]	(0.7004, 0.0836, 0)
	0.0001−100	−5	(0.8201, 0.0745)[c]	(0.9088, 0.0745, 0)

[a] (k_{cl}, τ_{cl}, ς_{cl}, θ_{cl}). [b] ($\bar{k}_c$, $\bar{\tau}_I$, $\bar{\tau}_D$), where $C_{out}(s) = \bar{k}_c(1 + 1/\bar{\tau}_I s + \bar{\tau}_D s)$. [c] ($k_{cl}$, τ_{cl}).

Table 3. Proposed Controller Parameters

process	$Q_1(s)$[a]	$Q_2(s)$[b]
WB	(1.3290, 2.0774)/(1.3290, 4.2073)	(0.7771, 4.2073, 0.3159)
	(5.0274, 2.8824)/(5.0274, 6.8937)	(−0.1010, 6.8937, 0.7293)
WW	(34.205, 8.2085)/(34.205, 16.888)	(56.480, 16.885, 2.0258)
	(58.205, 7.8549)/(58.205, 17.235)	(−22.839, 17.235, 3.3771)
OR	(6.6781, 2.9162)/(6.6781, 6.1748)	(1.5642, 6.1748, 1.0815)
	(6.3971, 2.5776)/(6.3971, 5.3524)	(−0.3210, 5.3524, 1.1952)
UB	(0.2139, 2.0267)/(0.2139, 5.6037)	(2.5543, 5.6037, 0.0382)
	(0, 0.0836)/(0, 0.2030)	(3.8176, 0.1565, 0)
	(0, 0.0745)/(0, 0.1565)	(−8.5020, 0.2030, 0)

[a] (α_1, α_2)/(β_1, β_2). [b] (k_c, τ_I, τ_D).

Downloaded by CHINESE ACAD SCI CAOS CONSORT on June 29, 2009
Published on May 17, 2002 on http://pubs.acs.org | doi: 10.1021/ie0102347

cesses. In multiloop 2DOF control systems, feedback parts of $Q_2(s)$ are more important because they are harder to design than the set-point filter parts of $Q_1(s)$. Our primary object of this study is to design excellent $Q_2(s)$. Only the feedback parts in the proposed control systems can also be used. These 1DOF control systems without the set-point filter, $Q_1(s)$, show peaks in set-point responses for some processes, but it is easy to design the set-point filters by some other methods to remove peaks in set-point responses. Methods to design SISO 2DOF control systems which can be applied easily to the design of multiloop control systems are few.

Unstable Batch (UB) Reactor. The proposed method can be applied to unstable processes including integrating processes stabilizable by a P control system. To illustrate this, the proposed method is applied to the following UB reactor problem:[14,15]

$$G(s) = \frac{1}{d(s)} \times \begin{bmatrix} 29.2s + 263.3 & -(3.156s^3 + 32.67s^2 + 89.93s + 31.81) \\ 5.676s^3 + 42.67s^2 - 68.84s - 106.8 & 9.43s + 15.15 \end{bmatrix},$$
$$d(s) = s^4 + 11.67s^3 + 15.75s^2 - 88.31s + 5.514$$

For this process, P controller gains calculated by the inverse Nyquist array method[14] are used. The diagonal elements of the inner P control system are approximated by the first-order system. Because there are no time delay terms, the first-order models are sufficient to approximate the closed P control system. The IMC method is applied to obtain PI controllers of $C_{out}(s)$. Tables 2 and 3 show the control systems obtained. The proposed control systems are compared with the multiloop PI control system in work by Green and Limebeer.[15] Better control responses are obtained as in Figure 6.

5. Conclusion

The IMC method can be used to design multiloop control systems. Each loop in multiloop control systems can be designed for the paired transfer functions by the IMC−PID method, and effects of the interactions can be compensated for by adjusting its design parameters.

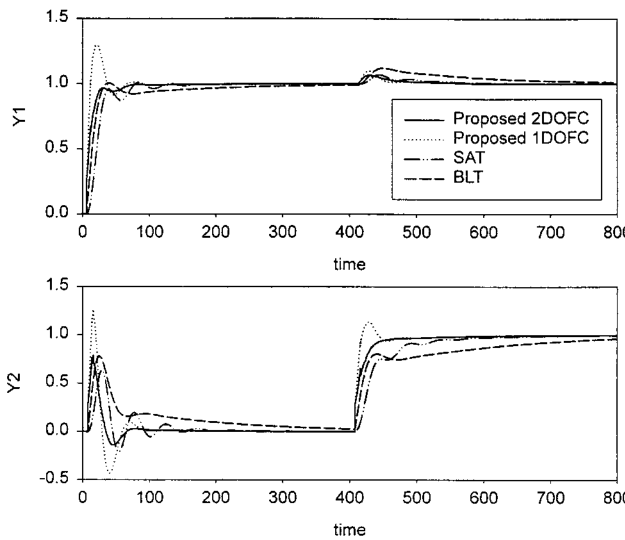

Figure 4. Step set-point responses for the WW column.

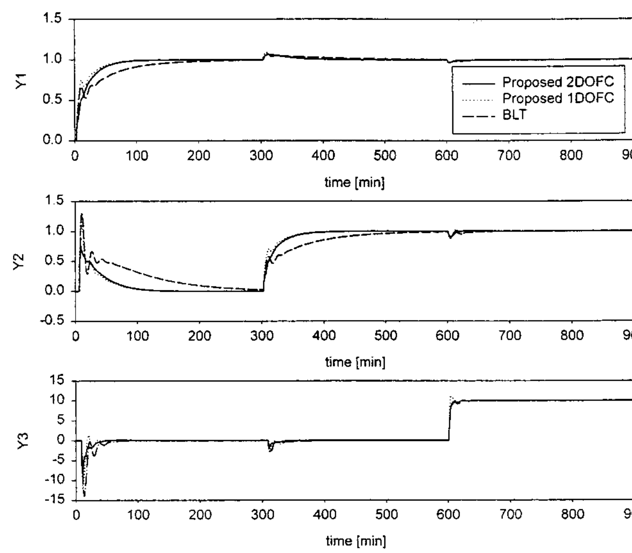

Figure 5. Step set-point responses for the OR column.

This method is as simple as the well-known BLT method and the sequential loop closing method. However, for some processes, simple adjustment of the design parameter of each loop may not be sufficient. To complement this, a two-step method modifying the IMC−PID method is proposed for the design of multiloop control systems. A proportional control system is designed first, and then a PID control system is designed for the closed-loop system compensated for by the P control system. Simulations show that the proposed method can reduce disadvantages in some other simple methods such as BLT that some loops are sluggish. The method can also

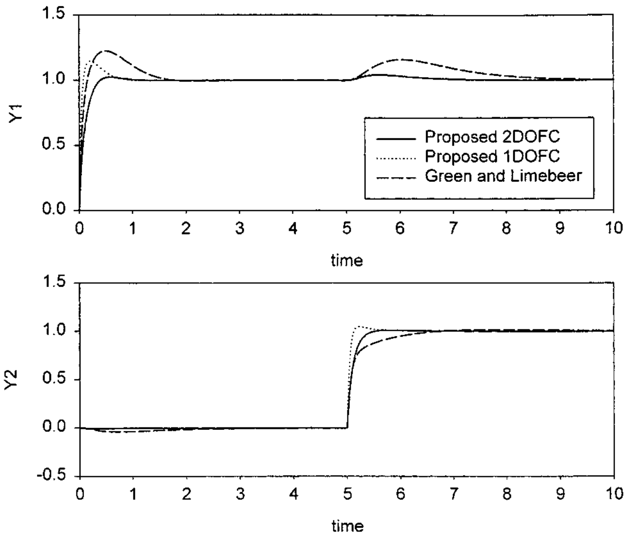

Figure 6. Step set-point responses for the UB reactor.

be applied to unstable processes stabilizable by P control systems including integrating processes.

Acknowledgment

The financial support by KOSEF under Grant 2000-1-3700-006-1 is gratefully acknowledged.

Literature Cited

(1) Morari, M.; Zafiriou, E. *Robust Process Control*; Prentice Hall: Englewood Cliffs, NJ, 1989.

(2) Hovd, M.; Skogestad, S. Improved independent design of robust decentralized controllers. *J. Process Control* **1993**, *3*, 43−51.

(3) Lee, J.; Choi, J. Y. Design of Multiloop PI Controllers. *KIChE J.* **1993**, *31*, 272 (Korean).

(4) Kwak, H. J.; Sung, S. W.; Lee, I. On-line Process Identification and Autotuning for Integrating Processes. *Ind. Eng. Chem. Res.* **1997**, *36*, 5329.

(5) Åström, K. J.; Hägglund, T. *PID Controllers: Theory, Design, and Tuning*; ISA: Research Triangle Park, NC, 1995.

(6) Luyben, W. L. Simple Method for Tuning SISO Controllers in Multivariable Systems. *Ind. Eng. Chem. Process Des. Dev.* **1986**, *25*, 654.

(7) Loh, A. P.; Hang, C. C.; Quek, C. K.; Vasnani, V. U. Autotuning of Multivariable Proportional−Integral Controllers Using Relay Feedback. *Ind. Eng. Chem. Res.* **1993**, *32*, 1002.

(8) Shen, S. H.; Yu, C. C. Use of Relay-Feedback Test for Autotuning of Multivariable Systems. *AIChE J.* **1994**, *40*, 627.

(9) Sung, S. W.; Lee, I. Limitations and Countermeasures of PID Controllers. *Ind. Eng. Chem. Res.* **1996**, *35*, 2596.

(10) De Paor, A. M.; O'Malley, M. J. Controller of Ziegler−Nichols Type for Unstable Process with Time Delay. *Int. J. Control* **1989**, *49*, 1273.

(11) Park, H. I.; Sung, S. W.; Lee, I. B.; Lee, J. On-line Process Identification Using the Laguerre Series for Automatic Tuning of the Proportional−Integral−Derivative Controller. *Ind. Eng. Chem. Res.* **1997**, *36*, 101.

(12) Grosdidier, P.; Morari, M. Interaction Measure Under Decentralized Control. *Automatica* **1986**, *22*, 309.

(13) Lee, J.; Cho, W.; Edgar, T. F. Multiloop PI Controllers Tuning for Interacting Multivariable Processes. *Comput. Chem. Eng.* **1997**, *22*, 1711.

(14) Rosenbrock, H. H. *Computer-Aided Control System Design*; Academic Press: New York, 1974.

(15) Green, M.; Limebeer, D. J. N. *Linear Robust Control*; Prentice Hall: Englewood Cliffs, NJ, 1995.

Received for review March 12, 2001
Revised manuscript received November 2, 2001
Accepted April 5, 2002

IE0102347

Downloaded by CHINESE ACAD SCI CAOS CONSORT on June 29, 2009
Published on May 17, 2002 on http://pubs.acs.org | doi: 10.1021/ie0102347