A New Direct-Synthesis Tuning Method for PI-Controllers

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A new efficient tuning method for proportional-integral (PI) controllers is proposed using overdamped closed-loop dynamics of the system. In line with other direct-synthesis and IMC methods, this new approach uses the desired closed-loop response to satisfy usual control and tuning objectives, but unlike the most other tuning methods hitherto-reported for PID controllers, it does not require that a process model be identified. Yet this new direct-synthesis (NDS) method is capable of making the controller perform the dual control functions of both good set-point tracking and disturbance rejection. Furthermore, it turns out that the new tuning method works equally well for difficult cases like large time delay and nonminimum phase processes. Finally, it can be said that this NDS method can be easily implemented and understood by the plant operating personnel because it has been developed emphasizing its on-site utility.

On propose une nouvelle méthode de réglage efficace pour des contrôleurs de type proportionnel-intégral (PI) qui fait appel à la dynamique en boucle fermée sur-amorties du système. À l'instar d'autres méthodes IMC et par synthèse directe, cette nouvelle approche utilise la réponse en boucle fermée désirée pour répondre aux objectifs de régulation et de réglage habituels, mais contrairement à la plupart des autres méthodes de réglage signalées jusqu'à présent pour des contrôleurs PID, il n'est pas nécessaire de définir un modèle de procédé. Pourtant cette nouvelle méthode par synthèse directe (NDS) permet au contrôleur d'exécuter les doubles fonctions de régulation du suivi du point de consigne et du rejet des perturbations. En outre, il s'avère que cette nouvelle méthode de réglage fonctionne bien également dans les cas difficiles comme les procédés à retard important ou à phase non minimum. Enfin, on peut dire que la méthode NDS peut être facilement introduite et comprise par le personnel d'exploitation car lors de sa conception une grande attention a été portée à sa fonctionnalité en usine.

Keywords: direct-synthesis tuning method, lead-lag element, overdamped response, PI-controllers.

The three-mode proportional-integral-derivative (PID) controller is recognized as most useful in chemical industries due to its good performance and high robustness for its simplicity. For the past several decades extensive research has been carried out to develop efficient tuning methods for this PID controller: frequency-domain tuning methods without process models (Ziegler and Nichols, 1942; Åström and Hägglund, 1988), model-based tuning methods (Cohen and Coon, 1953; Lopez et al., 1967); Smith et al., 1975; Morari and Zafiriou, 1989), and on-line tuning methods with closed-loop identification (Yuwana and Seborg, 1982; Lee et al., 1990). All these methods are effective for typical processes, but yet need further developments to fully satisfy general tuning criteria for chemical processes, such as: (1) no open-loop identifications, if possible; (2) no large overshoots during the period of identification; (3) easy and intuitive tuning procedures without requiring deep knowledge of control; (4) both of fast disturbance rejection and good set-point tracking, and (5) robustness against the uncertainties in the parameter values.

The purpose of this study is to propose a practical tuning method which is capable of satisfying the above criteria reasonably well. Specifically, a PI controller is designed using overdamped closed-loop response, not the underdamped response (Yuwana and Seborg, 1982) nor the ultimate cycling response (Ziegler and Nichols, 1942). Then the desired closed-loop time constant is used as the tuning factor in the same fashion as in the direct-synthesis method (Smith et al., 1975) and the IMC method (Morari and Zafiriou, 1989), but without an open-loop process model. A lead-lag function is included to make the controller perform both the good set-point tracking and the fast disturbance rejection, which constitutes another advantage of the method. A similar approach has been applied to the controller tuning of unstable processes (Jung et al., 1989). The proposed NDS method has been studied with simple processes, as well as with difficult ones possessing large time delay or nonminimum phase characteristics. The results are then compared with those by other tuning methods.

Theory of the New Direct-Synthesis (NDS) Method

The NDS tuning method tunes the controller using desired closed-loop response, as in the direct-synthesis method (Smith et al., 1975), but unlike this method, the new method does without an explicit open-loop process model. This is possible because the overdamped closed-loop response, resulting from the initial controller settings, is used. In other words, first, sluggish overdamped response by conservatively setting the initial controller parameter values as normally practiced in the start-up operation is produced, and next, the valuable process information, like the closed-loop time constant and the time delay, is extracted from this sluggish response approximating the system by a first-order-plus-time-delay (FOPTD) functional relation. Then, the close-loop information is used directly for tuning the PI-controller

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without going through an open-loop process model identification procedure. This tuning procedure thus, is different from the on-line identification tuning methods (Yuwana and Seborg, 1982; and Lee et al., 1990, 1993), which identify certain first-order or second-order-plus-time delay models from the closed-loop response obtained from initial P-control trials. Therefore, in this method, there is no need to check the mismatch between real process and estimated open-loop process model.

The desired closed-loop response of a process with the conventional feedback control structure is as follows:

$$\left(\frac{C}{R}\right)_d = \frac{G_{cr}G_p}{1+G_{cr}G_p} \quad \text{(1)}$$

where C, R, G_{cr} and G_p are controlled variable, set-point variable, desired controller (servo control) transfer function and process transfer function, respectively. The desired controller is then expressed by:

$$G_{cr} = \left(\frac{1}{G_p}\right)\frac{\left(\frac{C}{R}\right)_d}{1-\left(\frac{C}{R}\right)_d} \quad \text{(2)}$$

Now, to explain the right-hand side of Equation (2), first, since in the proposed method the desired closed-loop response is assumed of the FOPTD form, it can be written that:

$$\left(\frac{C}{R}\right)_d = \frac{e^{-\theta_{dr}s}}{\lambda_{dr}s+1} \quad \text{(3)}$$

where λ_{dr} and θ_{dr} are the desired time constant and the desired time delay, respectively.
As for the process dynamics, the following relationship is obtained which is evaluated from the closed-loop response generated by rough initial setting of the controller based on similar existing processes or rule-of-thumb tuning experiences (Anderson, 1983):

$$G_p = \left(\frac{1}{G_{co}}\right)\frac{\left(\frac{C}{R}\right)_o}{1-\left(\frac{C}{R}\right)_o} \quad \text{(4)}$$

For the evaluation of Equation (4), two things are needed. First, G_{co} representing the PI-controller with the initial controller setting is given by:

$$G_{co} = K_c\left(1+\frac{1}{\tau_I s}\right) \quad \text{(5)}$$

with K_c and τ_I being the gain and the reset time of the PI-controller, respectively. Second, $(C/R)_o$, the initial over-damped FOPTD response, is expressed by:

$$\left(\frac{C}{R}\right)_o = \frac{e^{-\theta_o s}}{\lambda_o s+1} \quad \text{(6)}$$

with λ_o and θ_o being the initial time constant and the initial time delay, respectively.

Since the time delay is the same between the initial and desired responses, θ_{dr} is set equal to θ_o and an approximate Taylor expansion for this time delay term is introduced:

$$e^{-\theta_o s} \cong 1-\theta_o s \quad \text{(7)}$$

Then, with the substitution of Equations (3), (4), (6) and (7) into Equation (2), the following very simple, approximate expression for the controller is finally obtained:

$$G_{cr} \cong \left(\frac{\lambda_o+\theta_o}{\lambda_{dr}+\theta_o}\right)G_{co} \quad \text{(8)}$$

which with the best choice of λ_{dr} exhibits the controller tuned for servo control.

As Equation (8) shows, the open-loop process model is not used in this tuning equation and all the required information for tuning the desired controller can be obtained from the closed-loop response and the initial controller settings. More will be said about these initial tuning parameters, as to their effect on the finally tuned controller performance.

Next, let us proceed to the determination of the controller tuning for the load changes. In a similar fashion to Equation (1), the closed-loop response upon load changes is given by:

$$\left(\frac{C}{L}\right) = \frac{G_L}{1+G_cG_p} \quad \text{(9)}$$

where L and G_L are disturbance variable and disturbance transfer function, respectively.

From Equations (2), (3) and (7) it can be written that:

$$G_{cr}G_p = \frac{\left(\frac{C}{R}\right)_d}{1-\left(\frac{C}{R}\right)_d} \cong \frac{1-\theta_o s}{(\lambda_{dr}+\theta_o)s} \quad \text{(10)}$$

Since it is the same controller for the both purposes of set-point tracking and disturbance rejection, the $G_{cr}G_p$ of Equation (10) is used for the term G_cG_p in Equation (9) to have the following response for load changes.

$$\left(\frac{C}{L}\right)_o = \frac{G_L(\lambda_{dr}+\theta_o)s}{\lambda_{dr}s+1} \quad \text{(11)}$$

This response, however, cannot be totally desirable because the controller was tuned based on the servo control criteria, and so the tuning parameter of the controller has to be reset to make the closed-loop response become more desirable for load changes. The new desired response will then become

$$\left(\frac{C}{L}\right)_d = \frac{G_L}{1+G_{cl}G_p} \cong \frac{G_L(\lambda_{dl}+\theta_o)s}{\lambda_{dl}s+1} \quad \text{(12)}$$

where λ_{dl} is the new desired closed-loop time constant suitable for load changes.

Now the derivation of the controller for regulatory control is in order. From Equation (12),

$$G_{cl}G_p \cong \frac{1-\theta_o s}{(\lambda_{dl}+\theta_o)s} \quad \text{(13)}$$

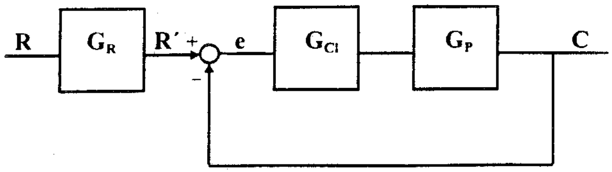

Figure 1 — Control structure of the NDS tuning method.

and from Equation (13) and Equation (10), the controller for the load changes is finally obtained

$$G_{cl} \cong \left(\frac{\lambda_{dr}+\theta_o}{\lambda_{dl}+\theta_o}\right)G_{cr} \cong \left(\frac{\lambda_o+\theta_o}{\lambda_{dl}+\theta_o}\right)G_{co} \qquad (14)$$

where the second equality is the result of the substitution of Equation (8).

Comparing Equations (8) and (14), it is noticed that the controllers tuned for set-point tracking and for disturbances rejection, i.e., G_{cr} and G_{cl}, take on the similar form. However, the two values of λ_{dr} and λ_{dl} can not be chosen at the same time for the single controller of the system. In order to make the controller perform the dual functions of servo and regulatory control simultaneously, one more component in the control structure is needed.

For this purpose, a lead-lag element is introduced to balance the closed-loop control performance of both servo and regulatory controls. The desired response of the controller (which has been tuned for load changes with G_{cl} of Equation (14) having the unknown element of G_R (as shown in Figure 1) for the set-point changes, is of overdamped nature and thus, is expressed by:

$$\left(\frac{C}{R}\right)_d = \frac{G_R G_{cl} G_p}{1+G_{cl}G_p} = \frac{e^{-\theta_o s}}{\lambda_{dr}s+1} \qquad (15)$$

The same controller without the G_R element exhibits the response as follows:

$$\left(\frac{C}{R'}\right)_d = \frac{G_{cl} G_p}{1+G_{cl}G_p} = \frac{e^{-\theta_o s}}{\lambda_{dl}s+1} \qquad (16)$$

where an overdamped response has also been assumed.

From Equations (15) and (16) then, G_R for the lead-lag element can be easily derived. This lead-lag element is a similar concept to the set-point filter of the two-degree of freedom control structure:

$$G_R = \left(\frac{R'}{R}\right) = \frac{\lambda_{dl}s+1}{\lambda_{dr}s+1} \qquad (17)$$

The tuning of the PI-controller by the NDS method is now completed: Equation (14) for the fast disturbances rejection and Equation (17) for the good set-point tracking.

Examples of the New Direct-Synthesis Method

The procedure of the PI-controller tuning by the NDS method derived above is summarized as follows: (1) An over-damped closed-loop response, i.e., the initial response $(C/R)_o$, is obtained from the PI-controller whose two parameters, K_c and τ_I, are set roughly and conservatively based on existing process design data or reference parameter values; (2) The values of the process closed-loop information, λ_o and θ_o, are then extracted from this closed-loop response using Equation (6); (3) The determination of the parameter λ_{dl} (the desired closed-loop time constant of the controller) is performed using Equation (14) with λ_0 being the initial value from which smaller values are successively tried for λ_{dl} until the controlled response is about to go over the set point; (4) Next, the determination of the parameter λ_{dr} (the desired time constant of the lead-lag element) is similarly performed using Equation (17) with λ_{dl} being the initial value from which larger values are successively tried for λ_{dr} until the controlled response is about to go beyond the desired target range. The values of λ_{dl} and λ_{dr} determined this way are such that λ_{dr} is larger than λ_{dl} but smaller than λ_0. Hence in this method no open-loop process model is identified, but the controlled response is easily brought within the targeted range in a simple way by adjusting two parameters.

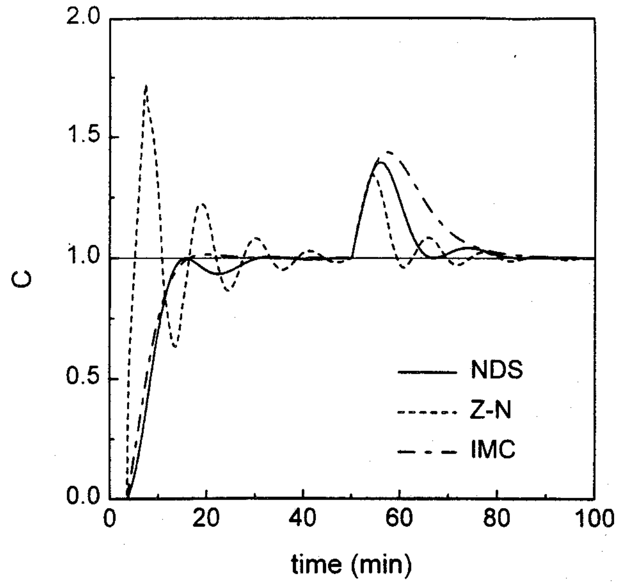

Figure 2 — Comparison of the tuning results of process 1.

This procedure is in line with the findings by other researchers (Seborg et al., 1989) that, for the desired control performance, the ITAE (integral of the time-weighted absolute error) load settings are generally less conservative than the ITAE set point settings. In other words, they agree with the results of this study, i.e., λ_{dl} being smaller than λ_{dr}. In addition, the idea of using the desired closed-loop time constant as a tuning parameter is also one of the widely used concepts practiced by both the direct-synthesis method (Smith et al., 1975) and the IMC method (Morari and Zafiriou , 1989).

For the purpose of simulation, the same first-order-plus-time-delay (FOPTD) process used by Seborg et al. (1989) has been adopted as the process 1 in this study.

$$G_p = \frac{4e^{-3.5s}}{7s+1} \qquad (18)$$

Figure 2 displays the comparison of the proposed NDS method with the IMC (Chien and Fruehauf, 1990) and

TABLE 1
Controller Settings for Process 1

Methods	Initial Settings	Controller Settings
Z-N	$K_U = 0.95$, $P_U = 12.0$	$K_C = 0.57$, $\tau_I = 6.0$, $\tau_D = 1.5$
IMC	$\tau_C = 4.5$	$K_C = 0.219$, $\tau_I = 7.0$
NDS	$K_C = 0.1$, $\tau_I = 7.7$	$\lambda_0 = 15.1$, $\theta_0 = 3.6$, $\lambda_{dr} = 5.5$, $\lambda_{dl} = 1.0$
NDS	$K_C = 0.13$, $\tau_I = 10.0$	$\lambda_0 = 13.4$, $\theta_0 = 3.6$, $\lambda_{dr} = 5.2$, $\lambda_{dl} = 0.7$

TABLE 2
Controller Settings for Process 2

Methods	Initial Settings	Controller Settings
Y-S	$K_C = 1.0$	$K_C = 1.210$, $\tau_I = 7.04$, $\tau_D = 1.76$
Lee et al.	$K_C = 1.5$	$K_C = 0.812$, $\tau_I = 4.33$, $\tau_D = 1.30$
NDS	$K_C = 0.3$, $\tau_I = 4.0$	$\lambda_0 = 9.2$, $\theta_0 = 4.4$, $\lambda_{dr} = 4.7$, $\lambda_{dl} = 4.0$

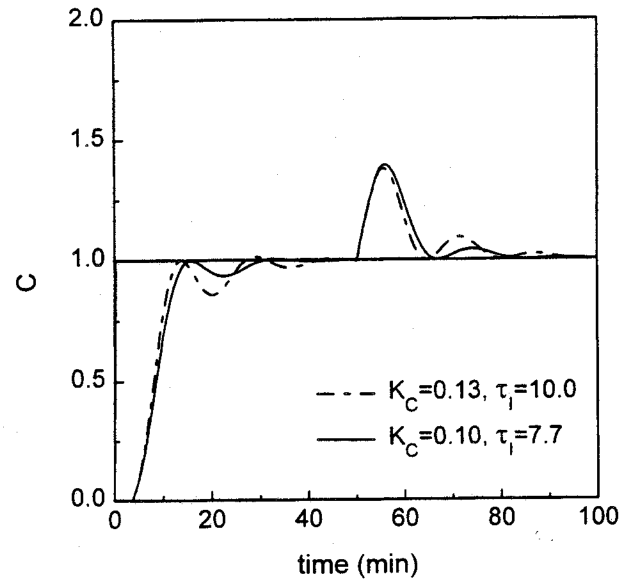

Figure 3 — Robustness of the NDS method for process 1.

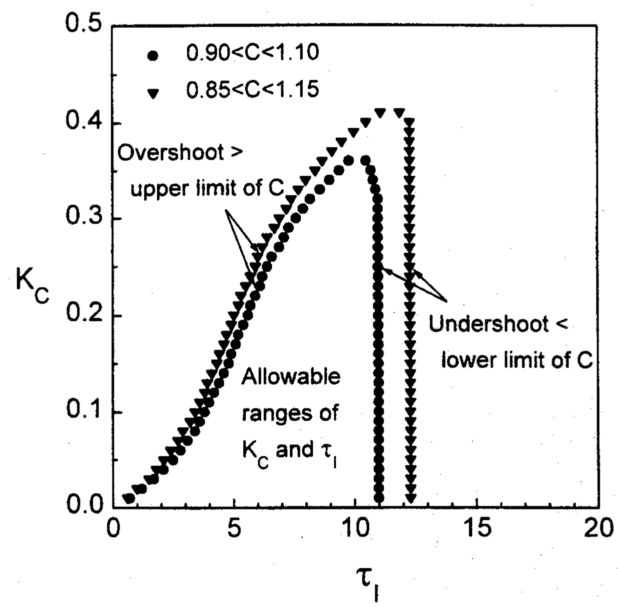

Figure 4 — Allowable ranges of the initial controller settings for process 1.

Ziegler-Nichols (Seborg et al., 1989) methods while Table 1 shows the controller settings by these three methods. The NDS method exhibits satisfactory performance in that it shows a faster disturbance rejection than the IMC method and doesn't show a strong servo control action as the Ziegler-Nichols method does.

In order to confirm the robustness of the NDS method, a comparison has been made, in Figure 3, between the different responses corresponding to two different initial controller settings of K_c and τ_I (10% and 43% increases from the reset time of the PI-controller). The examples of the ranges of the controller parameters guaranteeing the final control performance are displayed in Figure 4, showing that the allowable region gets larger as the desired strictness is relaxed with the more oscillatory closed-loop response. Figure 4 displays the computation results of the NDS method, starting from the initial settings of the controller, K_c and τ_I, when the targeted range of the controlled variable, C, is preset. The upper limit of C gives the left part of the curve in Figure 4 whereas the lower limit of C gives the right part of the curve. Thus, the allowable ranges for the controller settings are in the region between these two curves. This region represents the robustness of the NDS method against the initial controller settings, which are dependent on the knowledge of the process and on the nature of conservative start-up operation.

Whenever new tuning methods are proposed, there always arises a concern over the question whether they can handle the usual difficult processes (large time delays and nonminimum phase characteristics) frequently occurring in industrial processes. In this study, it is desired to evaluate the capability of the new proposed NDS method for these difficult processes. By selecting the same difficult processes discussed in the open literature, the performance of the NDS method is compared with those of other tuning methods.

Process 2 (having a large time delay):

$$G_p = \frac{e^{-3s}}{(s+1)^2(2s+1)} \quad (19)$$

This same process was studied by both Yuwana and Seborg (1982) and Lee et al. (1990). Table 2 shows the controller settings by the three methods. As Figure 5 shows, the NDS method exhibits favorable performance compared with those by other methods. The reason for this result lies in the fact that the NDS method adopts the process time delay directly to the tuning term as exhibited by Equation (8) and Equation (14), while other methods approximate this third-order-plus-time delay process with an open-loop FOPTD model and then use the model to tune the control parameters.

Process 3 (having nonminimum phase characteristics):

$$G_p = \frac{(-3s+1)e^{-s}}{(s+1)(5s+1)} \quad (20)$$

This nonminimum phase process proposed by Lee and Sung (1993) has been known as a difficult process to be identified with a simple first-order or second-order model

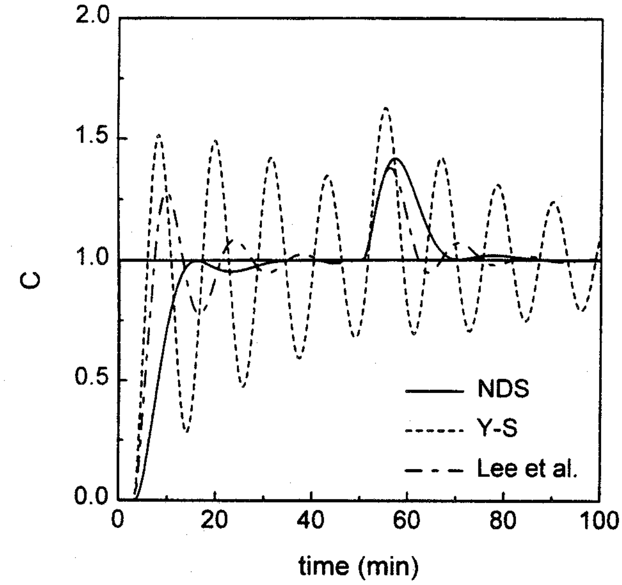

Figure 5 — Comparison of the tuning results of process 2.

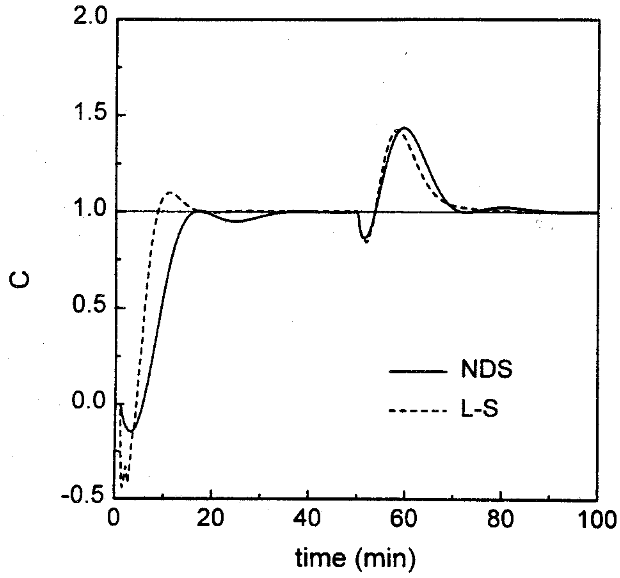

Figure 6 — Comparison of the tuning results of process 3.

because of its inverse characteristics. Figure 6 illustrates the controlled responses by the two methods using the values of Table 3, which shows both being satisfactory. In the NDS method, the inverse duration is treated as time delay with the inverse response being disregarded. One advantage of the NDS method is then, that the resulting control action shown in Figure 7 is smooth, as compared to that by the IMC method which is quite erratic during the inverse response period. This point is quite important in industrial applications where it is always desired to keep the control action non-erratic.

The NDS method, however, has its limitations for oscillatory second-order processes by showing not much improved control performance over the results of Yuwana and Seborg (1982) and Lee et al. (1990).

Conclusions

A simple NDS tuning method using overdamped closed-loop dynamics has been proposed. Without requiring the open-loop process model, the new method proves quite robust against the rough initial controller setting. The controller tuned by this NDS method is also capable of carrying out both the set-point tracking and fast disturbances rejection due to the lead-lag element introduced in the control structure. The new method has been tested in various processes published in the open literature, including difficult ones, and quite satisfactory results have been obtained for all of them. Also, since the NDS method has been derived from the experiences at the plants where large overshoots of the closed-loop response should be avoided while detailed process knowledge often lacking, and it can be easily implemented by the plant operating personnel.

TABLE 3
Controller Settings for Process 3

Methods	Initial Settings	Controller Settings
L-S	Relay Input	$K_C = 0.735$, $\tau_I = 4.89$, $\tau_D = 1.213$
NDS	$K_C = 0.5$, $\tau_I = 6.0$	$\lambda_0 = 6.0$, $\theta_0 = 5.0$, $\lambda_{dr} = 5.0$, $\lambda_{dl} = 2.2$

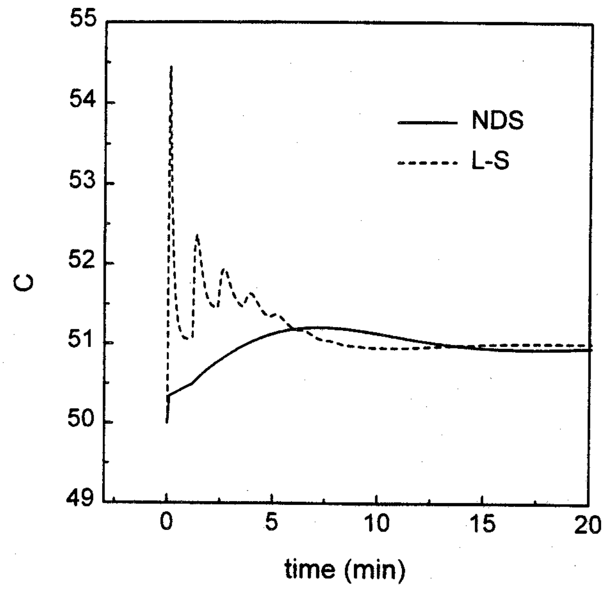

Figure 7 — Comparison of the controller outputs for process 3.

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Nomenclature

C = controlled variable
L = disturbance variable
R = set-point variable
G_{co} = transfer function of PI-controller with initial settings
G_{cl} = transfer function of PI-controller for desired regulatory control
G_{cr} = transfer function of PI-controller for desired servo control
G_L = disturbance transfer function
G_p = process transfer function
G_R = transfer function of lead-lag element for desired servo and regulatory control
K_c = controller gain of PI-controller

Greek letters

θ_I = integral time of PI-controller
θ_o = time delay of initial closed-loop response, (min)
θ_{dr} = time delay of desired closed-loop response, (min)
λ_o = time constant of initial closed-loop response, (min)
λ_{dl} = time constant (regulatory control) of desired closed-loop response, (min)
λ_{dr} = time constant (servo control) of desired closed-loop response, (min)
τ_I = integral time (reset time) of PI-controller, (min)

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