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불안정한 공정에 대한 온라인 공정 확인 및 자동 조절

On-Line Process Identification and Autotuning for Unstable Processes

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Abstracts In this paper, we first analyze the structural limitation of the conventional PID controller in controlling unstable processes through mathematical proof. To overcome this structural limitation, we add an internal feedback loop to the PID controller. Secondly, we obtain conditions when unstable processes can be stabilized by a controller through an analytical analysis. Finally, we propose a simple on-line process identification and autotuning method for unstable processes. Many simulation results show that, in spite of its simplicity, the proposed on-line process identification method provides good accuracy in modeling the unstable process and acceptable robustness to measurement noises and disturbances. Also, the proposed autotuner shows good control performances for both servo and regulatory problems.

Keywords Autotuning, Identification, PID controller, Unstable processes, Internal feedback loop.

1. INTRODUCTION

Proportional, integral, and derivative (PID) controllers are still used widely in industry because of their simplicity, robustness and successful practical applications. They have three adjustable parameters. To guarantee good control performances and stable closed-loop responses, three parameters should be tuned differently according to the dynamics of the process.

Many identification methods have been proposed to identify open-loop stable processes using the integrator plus time delay model, the first or the second order plus time delay model and many tuning rules have been developed for these models. Also, in recent years, many PID controller autotuning methods have been proposed to improve the control performance and simplify the tuning procedure of the PID controller.

However, almost all methods have been developed for open-loop stable processes. Until now, simple on-line identification methods to derive the transfer function of unstable processes and corresponding on-line tuning rules are rare. Kavdia and Chidambaram(1996) proposed an on-line identification method using a P controller as the test signal generator for an unstable process. However, it has a disadvantage that the initial gain of the P controller should be chosen appropriately to guarantee an underdamped closed-loop response and the identified model would show a poor accuracy for a large time delay process due to the first order Padé approximation in the theoretical development. De Paor and O'Malley(1989) developed a Ziegler-Nichols tuning rule to tune the P,PI and PID controller for unstable first order plus time delay processes. Semino(1994) proposed an automatic tuning method for PID controllers using the relay feedback and discussed stabilizability of unstable processes.

However, it should be noted that all control strategies using only the conventional PID controller have a structural limitation in controlling the unstable process(This will be discussed in section 2). Therefore, a new control strategy should be developed to control the unstable process more efficiently.

In this paper, we analyze the structural limitation of the conventional PID controller in controlling the unstable process. Based on it, we develop a control strategy using an internal feedback loop to overcome this limitation. We also derive conditions of the stabilizability for unstable processes analytically. Based on the conditions, we propose an on-line process identification method and corresponding PID tuning rule with a model reduction to tune the proposed PID controller automatically for the unstable process.

The proposed control strategy is very simple and guarantees on-line operation. At the same time, it shows superior control performances for both the set point tracking and the disturbance rejection problem compared with other previous control methods.

2. STRUCTURAL LIMITATION OF THE CONVENTIONAL PID CONTROLLER IN CONTROLLING UNSTABLE PROCESSES

In general, the PID controller is structurally suitable to control stable processes. However, it is inherently difficult for the PID controller to control the unstable process efficiently.

Consider the following desired trajectory(1), general linear time-invariant process transfer function(2), PID controller output(3) for the open-loop stable process controlled by the conventional PID controller and the differential equation(4) corresponding to the transfer function(2). Note that the following statements are valid for the first order desired trajectory of (1) as well as an over-damped high order desired trajectory.

$$y_{desired} = y_s - y_s \exp(-\frac{t}{\tau_{desired}}) \tag{1}$$

$$G_p(s) = \frac{b_m s^m + b_{m-1} s^{m-1} + \cdots + b_1 s + b_0}{a_n s^n + a_{n-1} s^{n-1} + \cdots + a_1 s + 1} \tag{2}$$

$$u(t) = k_c (y_s - y) + \frac{k_c}{\tau_i} \int_0^t (y_s - y) dt + k_c \tau_d \frac{d(y_s - y)}{dt} \tag{3}$$

$$a_n \frac{d^n y}{dt^n} + \cdots + y = b_m \frac{d^m u}{dt^m} + \cdots + b_0 u \tag{4}$$

where y_s, $y_{desired}$, $\tau_{desired}$ are a positive set point, a desired output trajectory and a desired time constant, respectively and a_i, b_i are arbitrary constants.

If a perfect tracking is assumed, the left-hand side of (4) can be rewritten as follows.

$$y_s + y_s \exp(-\frac{t}{\tau_{desired}})(\sum_{i=1}^{n} \frac{a_i(-1)^{i+1}}{(\tau_{desired})^i} - 1) \tag{5}$$

and the right-hand side of (4) can also be rewritten.

$$\frac{1}{\tau_i} b_0 k_c y_s \tau_{desired} + \exp(-\frac{t}{\tau_{desired}}) \sum_{i=1}^{m} \frac{A_i}{(\tau_{desired})^i} \tag{6}$$

where A_i are some constants.

By comparison of (5) and (6) it is clear that the left-hand and the right-hand sides of (4) have the same structure.

Therefore, it is possible to satisfy the equality of (4) by choosing appropriate tuning parameters. Thus, at least, the desired trajectory can be achieved from the viewpoint of the structure. However, for the unstable process, it can be known both sides of the equation have different structure. So the desired trajectory cannot be achieved with any tuning parameters.

In summary, although the structure of the PID controller is suitable to control the open-loop stable process it can not control unstable processes effectively. Therefore, it is obvious that first of all we must convert the unstable process to an open-loop stable process to control the unstable process by using the PID controller more effectively.

3. STABILIZABILITY OF UNSTABLE PROCESSES

When we consider unstable processes it is very important to know when unstable process can be stabilized. This problem has been considered in previous works(De Paor and O'Malley(1989), Kavdia and Chidambaram(1996), Semino(1994)) but their results are based on graphical approaches rather than systematic ones.

It is known from the Nyquist stability criterion that for a closed-loop system to be stable, the complete Nyquist curve of the open-loop process is to encircle the critical point(-1,0) anticlockwise the same number of times as the number of unstable poles. Figure 1 shows all possible patterns of the Nyquist curve of the following unstable process(9).

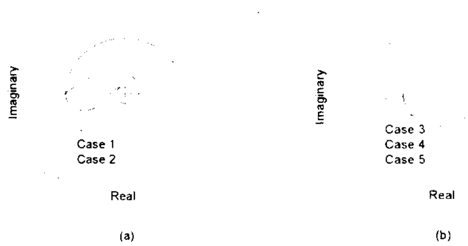


그림 1. 불안정한 공정에 대한 가능한 Nyquist curve 들.
Figure 1. Possible Nyquist curves of an unstable process.

By the viewpoint of Nyquist stability criterion, Nyquist curve must include negative imaginary portion at low frequency and anticlockwise encircling direction to stabilize the process by using a controller.
From Figure 1 we can extract two criteria for the stabilizability.

$$\lim_{\omega \to \varepsilon} \mathrm{Im}\{G_p(j\omega)\} < 0 \tag{7}$$

$$\lim_{\omega \to \varepsilon} \frac{\mathrm{AR}}{k} = \lim_{\omega \to \varepsilon} \frac{|G_p(j\omega)|}{k} < 1 \tag{8}$$

where ε is an infinitesimally small positive real number.
For example, we obtained stability condition for process (9) because it is the most general form of processes considered and result is given as (10).

$$G_p(s) = \frac{k(1+\tau_{d}s)\exp(-\theta s)}{(\tau s-1)(\tau_s s+1)} \tag{9}$$

$$\text{Necessary Conditions}\quad 0 < \theta < \tau + \tau_{d} - \tau_s,\quad \tau_{d}^2 < \tau^2 + \tau_s^2 \tag{10}$$

Notice that the result is the same as driven by previous papers.

In this section we derived criteria to test the stabilizability of the unstable process analytically. The derived conditions can be applied to understand the unstable process as well as to tune the controller.

4. PROPOSED ON-LINE PROCESS IDENTIFICATION STRATEGY

From now, we would present an on-line process identification method and a modified PID controller with tuning rules.

In the modeling of unstable processes, we use a relay to activate the process. From measured data sets, we can obtain a process model as a high order rational polynomial form of (2) by using least squares method. In this identification method, since we needs only the process output and input data, any type of the test signal generator can be used to activate the process only if it can stabilize the process.

The underlying concept of this identification method is very simple. Consider the following Laplace transforms.

$$G(s) = \frac{y(s)}{u(s)} \tag{11}$$

where $G(s)$ denote Laplace transforms of the process transfer function and can be obtained numerically as follows.

$$G(s_i) = \frac{y(s_i)}{u(s_i)} \tag{12}$$

$$y(s_i) = \sum_{t=0}^{t=t_{end}} \frac{\exp(-s_i t) - \exp(-s_i(t+\Delta t))}{s_i} y(t) \tag{13}$$

$$u(s_i) = \sum_{t=0}^{t=t_{end}} \frac{\exp(-s_i t) - \exp(-s_i(t+\Delta t))}{s_i} u(t) \tag{14}$$

$$i = 1,2,\cdots\cdots,ns \tag{15}$$

$$\frac{1}{\tau_{max}} = s_1 < s_2 < \cdots\cdots < s_{ns} = \frac{1}{\tau_{min}} \tag{16}$$

where Δt denote the sampling time. Here, we recommend the sampling time as small as possible to guarantee an acceptable accuracy in calculating.

It is noteworthy that the integral cannot be complete until $\exp(-s_i t)y(t)$ and $\exp(-s_i t)u(t)$ almost go to zero. We recommend the following equation as a criterion to end the integral.

$$\exp(-s_i t_{end}) < 0.0001 \tag{17}$$

To obtain a continuous model from the calculated $G(s_i)$'s, the following high order rational polynomial model is used.

$$G_m(s) = \frac{b_m s^m + b_{m-1}s^{m-1} + \cdots\cdots + b_1 s + b_0}{a_n s^n + a_{n-1}s^{n-1} + \cdots\cdots + a_1 s - 1} \tag{18}$$

Then least squares method minimizing the objective function(19) can be used to obtain the coefficients of (18) from the calculated $G(s_i)$'s.

$$\underset{b,a}{\mathrm{MIN}} \left[\begin{array}{l} \sum_{i=1}^{ns} \{a_n G(s_i)s_i^n + a_{n-1}G(s_i)s_i^{n-1} + \cdots + a_1 G(s_i)s_i \\ - b_m s_i^m - b_{m-1}s_i^{m-1} - \cdots - b_1 s_i - b_0 - G(s_i)\}^2 \end{array} \right] \tag{19}$$

In summary, from the controller output and the measured process output data (12),(13) and (14) can be calculated and then we can estimate the coefficients of (18) using least squares method to satisfy (19). In spite of simplicity of the proposed on-line process identification method, it shows good accuracy in modeling the unstable process.

5. PROPOSED CONTROL STRATEGY

As mentioned previously, the conventional PID controller can't control the unstable process effectively. Therefore, we propose a control structure as shown in Figure 2 to control the unstable process effectively. We use a PD controller as an internal feedback loop to convert the unstable process to the open-loop stable process. Then the PID controller can control the overall open-loop stable process efficiently as mentioned in the above analysis section.

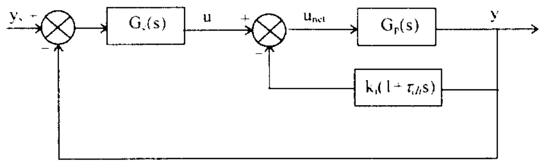


그림 2. 불안정한 공정을 제어하기 위한 제안된 제어 전략
Figure 2. Proposed control strategy to control an unstable process.

How the internal feedback loop converts the unstable process to an open-loop stable process can be shown by same procedure conducted in section 2. As shown in Figure 2, the overall process input is the summation of the PID controller output and the internal feedback signal as follows,

$$u_{net}(t) = u(t) - k_i\left(y(t) + \tau_{di}\frac{dy(t)}{dt}\right) \tag{20}$$

where k_i and τ_{di} represent gain and derivative time of the internal feedback loop, respectively.

To construct an overall open-loop stable process, we should tune the internal feedback loop. To do this, the high order process model $G_m(s)$ of (18) should be reduced to the following unstable model.

$$G_{r-m}(s) = \frac{ke^{-\theta s}}{(\tau s-1)(\tau_s s+1)} \tag{21}$$

(21) can be obtained by a simple model reduction method which is a slightly modified one of Sung and Lee(1996) and Levy(1959). Then using (22), the derivative time of the internal feedback loop is estimated.

$$\frac{\tau_{di}}{\tau} = X_1 + X_2\left(\frac{\theta}{\tau}\right) + X_3\left(\frac{\theta}{\tau}\right)^2 \tag{22}$$

$$X_1 = -0.003 + 0.648\left(\frac{\tau_s}{\tau}\right) - 2.284\left(\frac{\tau_s}{\tau}\right)^2 + 2.622\left(\frac{\tau_s}{\tau}\right)^3 - 0.961\left(\frac{\tau_s}{\tau}\right)^4 \tag{23}$$

$$X_2 = 0.245 - 1.041\left(\frac{\tau_s}{\tau}\right) - 13.672\left(\frac{\tau_s}{\tau}\right)^2 - 16.762\left(\frac{\tau_s}{\tau}\right)^3 + 5.147\left(\frac{\tau_s}{\tau}\right)^4 \tag{24}$$

$$X_3 = 0.169 + 0.829\left(\frac{\tau_s}{\tau}\right) - 9.363\left(\frac{\tau_s}{\tau}\right)^2 + 2.986\left(\frac{\tau_s}{\tau}\right)^3 + 7.380\left(\frac{\tau_s}{\tau}\right)^4 \tag{25}$$

Here, note that this tuning rule is developed for the stabilizable processes.

The proportional gain of the internal feedback loop is estimated by the following equation.

$$k_i = \frac{1}{\sqrt{|G_m(j\omega_u)(1+j\tau_{di}\omega_u)||G_m(0)|}} \tag{26}$$

$$\text{Optimal Gain Margin} = \frac{\sqrt{|G_m(0)|}}{\sqrt{|G_m(j\omega_u)(1+j\tau_{di}\omega_u)|}} \tag{27}$$

Here, (26) guarantees the optimal gain margin(for details, refer to De Paor and O'Malley(1989)) and (27) is the optimal gain margin of the process controlled by the internal feedback loop with gain of k_i. (22) is derived by solving the following optimization problem and fitting the obtained optimal data sets with dimensionless grouping.

$$\tau_{di\,optimal} = \underset{\tau_{di}}{\text{MIN}}\left|G_m(j\omega_u)(1+j\tau_{di}\omega_u)\right| \tag{28}$$

Here, $\tau_{di\,optimal}$ and ω_u denote the optimal value of the τ_{di} and the ultimate frequency of $G_m(s)(1+\tau_{di}s)$ and $G_m(s)$ is the high order model of (18). The objective function (28) is constructed to guarantee the maximum gain margin of (27).

After the tuning of the internal feedback loop using (22) and (26), the outer-loop PID controller should be tuned for the overall process composed of the high order model and the internal feedback loop. However, the PID controller tuning rules are usually based on the first or the second order plus time delay model rather than a high order model. Therefore, we must reduce the overall process to a low order plus time delay process. In this paper, we obtain the following reduced second order plus time delay model by using a model reduction method to tune the outer-loop PID controller parameters using a second order plus time delay tuning rule. That is,

$$G_{overall}(s) = \frac{G_m(s)}{1+k_iG_m(s)(\tau_{di}s+1)} \cong \frac{k_m\exp(-\theta_m s)}{\tau_m^2 s^2 + 2\tau_m\zeta_m s + 1} = G_{reduced}(s) \tag{29}$$

where k_m, θ_m, τ_m and ζ_m denote the static gain, time delay, time constant and the damping factor of the reduced model, respectively. In this step we used the model reduction method(Sung and Lee(1996)) to obtain the second order plus time delay model. Because we get the reduced second order plus time delay model we can tune the outer-loop PID controller by using the second order plus time delay tuning rule(Sung et al.(1996)).

This tuning rule was developed by fitting the optimal data sets obtained from the optimization with the Integral of the Time-weighted Absolute value of the Error(ITAE) as an objective function. Although it is composed of only several algebraic equations without any complicated numerical technique and the control results by this tuning rule are almost the same as those of the optimal tuning results.

In summary, a high order rational polynomial model $G_m(s)$ is obtained by the proposed identification method and then k_i and τ_{di} are tuned by the proposed tuning rule of (22) and (26) with the model reduction method. Finally the outer-loop PID controller is tuned by Sung et al.'s(1996) tuning rule with another model reduction method.

6. SIMULATION STUDY

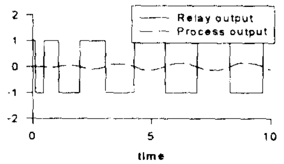
Example 1. Consider the following unstable time delay process including one unstable pole and one stable pole.

$$G_p(s) = \frac{2.0e^{-0.1s}}{(3s-1)(s+1)} \tag{30}$$

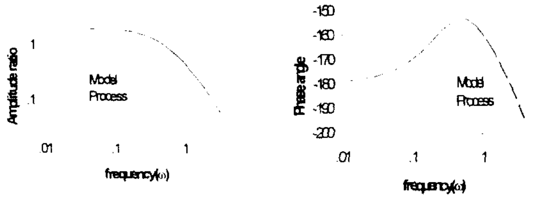
Figure 3(a) shows the activated process responses by a relay. The following polynomial process model is obtained by the proposed identification method.

$$G_m(s) = \frac{0.0019s^4 - 0.0987s^3 + 1.7226s^2 - 3.5663s + 2.0}{0.0983s^5 + 2.0900s^4 - 3.6841s^3 - 1.0552s^2 + 3.6888s - 1.0} \tag{31}$$

From Figure 3(b), we can recognize that the proposed on-line process identification method provides a good model accuracy, where $\tau_{min} = 0.2$ and $\tau_{max} = 0.8$ are chosen for the identification. Even though we choose $\tau_{min} = 0.2$ and τ_{max} from 0.4 to 8.0 or τ_{min} from 0.1 to 0.4 and $\tau_{max} = 0.8$ arbitrarily, the identification results are almost same.



(a)



(b)

그림 3. (a) Relay feedback 에 의해서 활성화 된 공정.
(b) 식별된 모델과 실제 공정의 Bode plot 들.
Figure 3. (a) Activated process responses by a relay feedback.
(b) Bode plots of the identified model and the actual process.

From these results and our experience in extensive simulations, we can conclude that the proposed identification method shows an acceptable robustness to the choice of τ_{min} and τ_{max}. However, it should be noted that if τ_{max} is chosen as a large value then s_1 of (17) becomes such a small value that a long identification time is needed to satisfy (17).

By the model reduction method. the following is obtained from (32).

$$G_{r-m}(s) = \frac{2.0021e^{-0.3059s}}{(3.0067s-1)(0.9967s+1)} \quad (32)$$

Now. with the obtained process model and the values of the internal feedback loop gain(k_i) and derivative time(τ_{di}). we obtain the following reduced second order plus time delay model by using the model reduction method.

$$G_{reduced} = \frac{0.1706 \cdot e^{-0.1108s}}{(0.4848)^2 s^2 + 2(0.4848)(0.3041)s + 1.0} \quad (33)$$

To show the accuracy of this model reduction method we compared Bode plots of the overall model with those of the reduced second order plus time delay model. From the result we can recognize that this reduction method show good accuracy. Since (33) is a common second order plus time delay model. the PID parameters can be determined for both the servo and the regulatory problems by employing the second order plus time delay tuning rule(Sung et al(1996)).

The tuning results are given below and the performances of the controller tuned by these parameters are shown in Figure 4 for the servo(a) and the regulatory(b) problems. respectively.

1) For the servo problem.

$$k_c = 7.5773,\ \tau_i = 0.3010,\ \tau_d = 0.7674 \quad (34)$$

2) For the regulatory problem.

$$k_c = 41.5377,\ \tau_i = 0.3523,\ \tau_d = 0.2457 \quad (35)$$

As shown in Figure 4. the proposed control strategy shows a superior control performance to the conventional PID controller for both the set point change and disturbance rejection problems. Here. the conventional PID controller is tuned by Ziegler-Nichols tuning rule(De Paor and O'Malley(1989)).

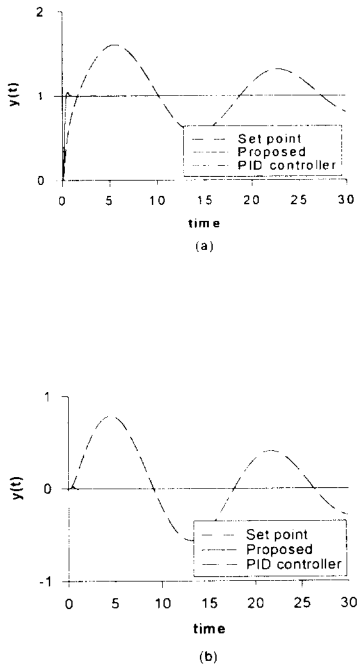


그림 4. 제안된 제어 전략과 일반적인 PID 제어기의 제어 결과.
(a) 설정 치 변화 (b) 외란 제거.

Figure 4. Control results of the proposed control strategy and the conventional PID controller.
(a) Set point change (b) Disturbance rejection

7. CONCLUSIONS

In this paper. we proposed a simple on-line process identification and autotuning method for the unstable process. It dose not require complicated numerical techniques such as optimization or iterative procedure. Also. the process model is estimated from only measured input-output data sets without any structural closed-loop information. Therefore. any type of test signal generator can be used only if it can stabilize the unstable process. From the simulation study we can conclude that the proposed identification method provides good model performances and robustness to measurement noises and disturbances.

Moreover. we showed that the conventional PID controller has a structural limitation in controlling the unstable process. Based on this analysis. we proposed a control strategy using an internal feedback loop to control the unstable process more efficiently and we added a derivative action to widen stabilizability range of the unstable process. Here. the internal feedback loop plays an important role in converting the unstable process to an open-loop stable process.

A model reduction method is introduced to tune the outer-loop PID controller easily. It reduces the overall transfer function to a second order plus time delay model so that usual second order plus time delay tuning rules can be used to tune the outer-loop PID controller. Also. the other model reduction method is proposed to reduce the high order process model to a simpler unstable process. From the reduced model. we can tune the derivative time of the internal feedback loop and infer the stabilizability. From simulation study and analysis. we can conclude that the proposed control strategy promises to contribute toward control problems of unstable processes.

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