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ON-LINE PROCESS IDENTIFICATION AND PID CONTROLLER AUTOTUNING

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Abstract – We propose a new and simple on-line process identification method for the automatic tuning of the PID controller. It does not require a special type of test signal generators such as relay or P controller only if the signals are persistently exciting. That is, a user can choose arbitrary signal generators such as relay, a P controller, the controller itself, pulse signal and step signal generator because it needs only the measured process output and the controller output. It can incorporate nonlinearities due to actuator saturation or manual mode operation during identification work and shows a good robustness to measurement noises, nonlinearity of the process and disturbances. The proposed autotuner combined with the identification method and tuning rule using a model reduction shows good control properties compared with previous autotuning methods.

Key words: Process Identification, Autotuning, PID Controller, Relay

INTRODUCTION

Even though many advanced control strategies have been developed in last decade, the PID controller has most contributed to solving major control problems in industry. It has been recognized as the simplest and much robust controller. Moreover, it is very familiar to the field operator.

However, it is not easy to tune the parameters of the PID controller when the process has relatively large time delay compared with the time constant or it is high order. The tuning of the PID controller using the continuous cycling, the process reaction curve or trial and error method involve tedious procedure or stability problem. The continuous cycling method uses the Ziegler-Nichols (ZN) tuning method so that frequently the tuning performance can be poor for an underdamped process, integrating process or very large time delay process. Moreover, it needs repetitive procedure and it is not recommendable for a dangerous or sensitive process because it puts the process on the border of the stability. In the process reaction curve method, it is difficult to determine the inflection point and the magnitude of the step input. Also, because it is an open-loop step test, it is difficult to identify the operating frequency region of the controller. To overcome these drawbacks, many simple on-line closed-loop identification methods have been proposed to tune PID controllers automatically and efficiently.

Åström and Hägglund [1984] identified ultimate process information from a relay feedback test to tune the PID controller automatically. Here, the relay is used as a test signal generator to activate the process. It guarantees a stable closed loop response for the open loop stable process and is commercially available. Li et al. [1991] obtained parametric models from two relay feedback tests. Lee and Sung [1993] obtained the first order plus time delay model from a relay feedback test combined with a proportional (P) controller. Their method provides the exact model for a first order plus time delay process. Sung et al. [1995] proposed a modified relay feedback method to obtain more accurate ultimate data than that of Åström and Hägglund's method [1984] by reducing high order harmonic terms. Sung et al. [1996] proposed a new identification method using the second order plus time delay model to approximate the process more accurately and a simple tuning rule for the second order plus time delay model. Shen and Yu [1994] and Loh et al. [1993] extended these automatic tuning concepts to the multi-input and multi-output (MIMO) case using the sequential loop closing concept. Lee et al. [1993] proposed an on-line identification method using Åström and Hägglund's [1984] concept to control the pH processes. Above-mentioned autotuning methods using the relay are very simple and efficient. However, the identified information is only one point on the Nyquist plot (usually, ultimate information) so frequently, a good control performance can't be guaranteed.

Yuwana and Seborg [1982] proposed a P control method to obtain the first order plus time delay model using few transient data points. It used the Proportional (P) controller to activate the process. It was improved by Jutan and Rodrigez [1984], Lee [1989], Chen [1989] and Sung et al. [1994], Lee et al. [1990] suggested a P control method to identify the process using the second order plus time delay model. To estimate the parameters of the PID controller, a frequency domain tuning method based on the methods of Edgar et al. [1981] and Harris and Mellichamp [1985] is applied, yielding a good controller setting. Sung and Lee [1995] applied Yuwana and Seborg's [1982] autotuning concept to obtain the titration curve of the pH process automatically. In this method, the proportional gain of the P con-

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troller (test signal generator) should be tuned to guarantee an underdamped closed loop response. This is a critical disadvantage in the implementation.

All the previous methods should use a special test signal generator such as P controller or relay. Therefore, the PID controller can't control the process continuously moreover, it is not easy to determine the magnitude of the relay feedback and the initial proportional gain of the P controller. The identified models of previous methods show poor robustness to measurement noises because the methods utilize only several dominant data points.

We propose a new identification method to automatically tune the PID controller. The proposed identification method does not require a special test signal generator such as P controller or relay. That is, a user can utilize arbitrary test signal generator such as the PID controller itself, relay, P controller, pulse signal or step signal generator because only the controller output and the measured process output are required to identify the process. Also, the proposed identification method can incorporate nonlinearities resulted from actuator saturation or manual mode operation during the identification work. Additionally, the method can provide the model needed to design other type-controllers such as the Dynamic Matrix Control (DMC) or Model Algorithmic Control (MAC) since we can easily estimate the finite impulse/step response model from the identified continuous model.

PROPOSED ON-LINE PROCESS IDENTIFICATION METHOD

Many system identification literatures usually treat discrete-time domain approaches such as the auto-regressive integrated moving average model with exogeneous input (ARIMAX model) identified by linear estimators such as the recursive least squares method, prediction error method, instrumental variable method etc. The discrete-time model can represent the deterministic and stochastic processes efficiently and then it can be used for predictive control strategies such as the Generalized Predictive Control (GPC), Generalized Minimum Variance (GMV) Controller. However, a continuous-time model is required to tune the PID controller. Moreover, the model should be a low order plus time delay model to estimate the parameters of the PID controller using usual tuning rules. We would introduce a new identification and model reduction method to tune the PID controller automatically.

Consider the following Laplace transform.

$$y(s)=\int_0^\infty \exp(-st)\,y(t)\,dt \tag{1}$$

$$u(s)=\int_0^\infty \exp(-st)\,u(t)\,dt \tag{2}$$

$$G(s)=\frac{y(s)}{u(s)} \tag{3}$$

where, y(s), u(s) and G(s) denote Laplace transforms of the process output, controller output and transfer function, respectively. The underlying identification concept is very simple. (1) and (2) are estimated by numerical integral technique for several positive real s values and the corresponding G(s)'s are calculated from (3) and finally, G(s)'s are used to determine the adjustable parameters of a specified model using the least squares method.

(1) and (2) can be calculated by (4) and (5) numerically. These numerical integration formula are derived by assuming the process output and input are constant from t to t+Δt. Other integration formula can be also used like the rectangular, Simpson and trapezoidal method.

$$y(s_i)=\sum_{t=0}^{t=t_{end}} \frac{\exp(-s_i t)-\exp(-s_i(t+\Delta t))}{s_i}\,y(t) \tag{4}$$

$$u(s_i)=\sum_{t=0}^{t=t_{end}} \frac{\exp(-s_i t)-\exp(-s_i(t+\Delta t))}{s_i}\,u(t) \tag{5}$$

$$G(s_i)=\frac{y(s_i)}{u(s_i)} \tag{6}$$

$$i=1,2,\cdots,ns \tag{7}$$

$$s_1=1/\tau_{max}<s_2<s_3\cdots<s_{ns}=1/\tau_{min} \tag{8}$$

where, n_s, and Δt denote the number of s_i and sampling time, respectively and s_i are located with equal interval. (8) represents the recommended upper and lower boundary values of s_i.

In (1) and (2), the Laplace transform of a signal ($y(s_i)$ or $u(s_i)$) means the integral of the signal (y(t) or u(t)) weighted by a weight function $\exp(-s_i t)=\exp(-t/\tau_i)$. Therefore, roughly speaking, we can say that the signals below τ_{max} are mainly considered to estimate the process model. It is notable that $G(s_i)$ is exactly the same as the numerical value of the process transfer function if the integration is exact. We will fit the adjustable parameters of the model using the calculated $G(s_i)$ in the s domain.

We recommend the sampling time as small as possible to guarantee a continuous-time system and an acceptable accuracy in calculating the integrals of (1) and (2). From many simulation studies, we recognize that if the ratio of the time constant to the sampling time is larger than 20, then an acceptable accuracy can be guaranteed.

If the process is activated by the PID controller, we recommend τ_{min}, τ_{max} values as the time delay and the time constant of the closed loop response. Here, the time delay term can be inferred by measuring the time corresponding to a specified small deviation of the process output from initial value. Also, dominant time constant can be determined by the time of the process output corresponding to 63% of the set point or steady state. On the other hand, if the process is activated by the relay, τ_{min} and τ_{max} values can be chosen as the time delay and the half-period of the closed loop response. But, it is notable that various τ_{min} and τ_{max} values different from the above recommended specifications result in almost same model.

It should be noted that the integral from zero to infinite can not be obtained until $\exp(-s_1 t)y(t)$ and $\exp(-s_1 t)u(t)$ almost go to zero. We recommend the following equation as the criterion to end the integral.

$$\exp(-s_1 t_{end})<0.0001 \tag{9}$$

Here, if we choose τ_{max} as a very large value, the identification time t_{end} would be very long to satisfy (9). On the other hand, too much information of the signal (the signal information after t_{end}) would be lost if we choose τ_{max} (equivalently, t_{end}) as a very small value.

To obtain a continuous model from the calculated $G(s_i)$'s, the following model can be used to model the open loop stable process.

$$G_m(s) = \frac{n_m s^m + n_{m-1} s^{m-1} + --- + n_1 s + n_o}{d_n s^n + d_{n-1} s^{n-1} + --- + d_1 s + 1} \quad (10)$$

Then, an off-line (batch) least squares method minimizing the following objective function can be used to obtain the coefficients of (10) from the calculated $G(s_i)$'s.

$$\underset{d,n}{\mathrm{MIN}} \left[\begin{array}{l} \sum_{i=1}^{ns} \{ d_n G(s_i) s_i^n + d_{n-1} G(s_i) s_i^{n-1} + --- + d_1 G(s_i) s_i \\ - n_m s_i^m - n_{m-1} s_i^{m-1} ------ n_1 s_i - n_0 + G(s_i) \}^2 \end{array} \right] \quad (11)$$

where, d and n denote vectors composed of the coefficients of denominator and numerator, respectively. Again, it is notable that the proposed identification method of (11) is just a curve fitting to approximate the numerical value of the process transfer function in terms of various real s values if the integration of (4) and (5) is sufficiently accurate.

To prevent singularity in the least squares method, at least, ns should be larger than n+m. On the other hand, the accuracy and robustness would be enhanced as ns increases, but the computing load is also heavier. We recommend $ns \geq 6(n+m)$ with equal interval between s_i's on the basis of the experiences in the use of the least squares method. The proposed identification method is more complicate than previous autotuning methods. However, it needs not any complicated numerical techniques and it can be implemented by using present available computing power without any problem.

In summary, from the controller output and the measured process output data, (4), (5) and (6) can be calculated and then we can estimate the coefficients of (10) using the least squares method satisfying (11). Next, the model (10) can be reduced to the second order plus time delay or the first order plus time delay model to tune the PID controller using usual tuning methods such as Internal Model Control (IMC), the Integral of the Time weighted Absolute value of the Error (ITAE), Cohen-coon methods.

Here, it should be noted that the proposed identification method can be applied to the open loop stable process being initially in a steady state. Therefore, processes subject to continuing disturbances or unexpected perturbations can't be incorporated by the proposed identification method.

1. Effects of τ_{min} and τ_{max} Values and Time Delay

The proposed identification strategy is to minimize the error in the Laplace domain between the process transfer function and the model of (10). That is, if the numerical integral is accurate, the proposed method is simply to approximate the process transfer function by adjusting the model parameters of (10) using the numerical values of the process transfer function corresponding to several real positive s values.

The method to approximatė the process in the Laplace domain is not a new concept. For a long time, we have been used the same concept to approximate the time delay term using the Taylor's series or Padé approximation and to reduce the high order model using continued fraction expansion and truncation [Chen and Shieh, 1968; Chen and Shieh, 1970; Chen et al., 1971] and for simplification via moments [Gibilaro and Lees, 1969; Papadourakis et al., 1989]. The proposed method simply extends the concept to the identification problem. Roughly speaking, only difference between the above-explained methods and the proposed method is the choice of the range of s values. For example, the Talyor's series approximate the process transfer function around s=0. On the other hand, the proposed method approximate the part of the process corresponding to the range $1/\tau_{max} \leq s \leq 1/\tau_{min}$.

To analyze the effects of the parameters τ_{min} and τ_{max}, consider the following transfer function

$$G_p(s) = \frac{\exp(-\theta s)}{(s^2+2s+1)} \quad (12)$$

The proposed identification method is equivalent to estimate the model transfer function of (10) by minimizing the following criterion of (13) using the least square method of (11) if the numerical integration is sufficiently accurate. Here, $G_p(s_i)$ is just the numerical value of the process (12) for a positive $s=s_i$ value.

$$\underset{n,d}{\mathrm{MIN}} \sum_{t=1}^{ns} \{G_p(s_i) - G_m(s_i)\}^2 \quad (13)$$

i) We estimated the model of (10) corresponding to the process of (12) for τ_{max}=0.5, τ_{max}=5.0, τ_{max}=50.0 with $\tau_{min}=\theta$, θ=0.1, n=5 and m=4 to inspect the effects of various τ_{max} values. Bode plots of the process and the estimated models for various τ_{max} values are shown in Fig. 1. The estimated models show good accuracy and are almost same for the various τ_{max} values. From the results, we recognize that the estimated model are not almost affected by the chosen τ_{max} value only if n and m are

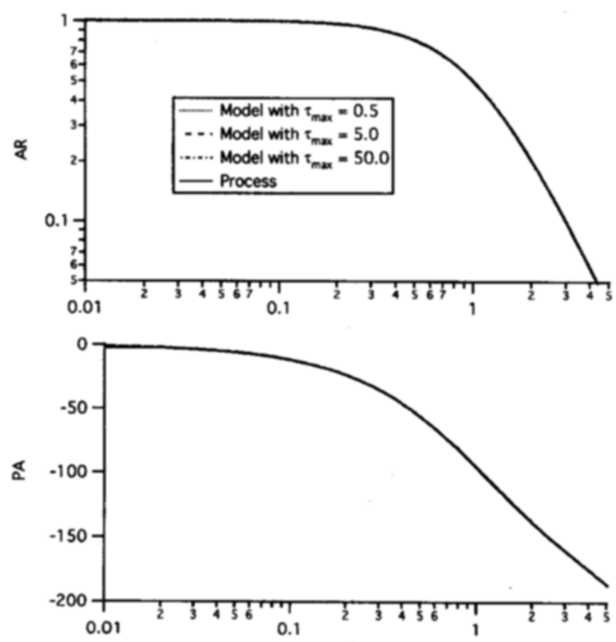

Fig. 1. Bode plots of the process and the models for various τ_{max} values.

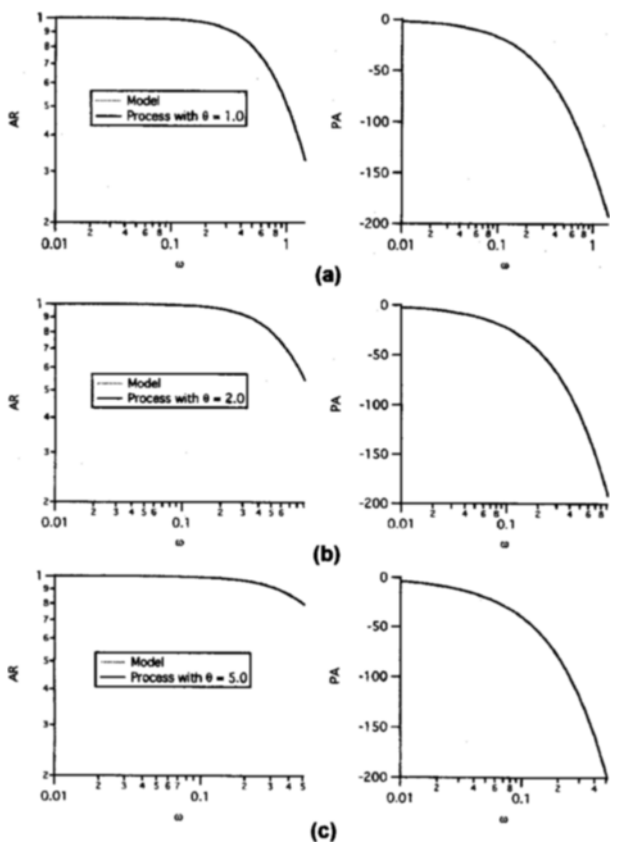

Fig. 2. Bode plots of the process and the model for various time delays.

chosen as sufficiently large values. However, if τ_{max} value is less than about 2 times τ_{min}, the estimated model frequently shows a poor performance. As τ_{max} and τ_{min} are closed, the independency of the data sets $G(s_i)$'s decreases so the sensitivity to structural plant/model mismatches would increase and many informations would be lost. Therefore, we recommend the following

$$\tau_{min} = \text{time delay}$$

$$\tau_{max} = \max(6 \text{ times } \tau_{min},\ \text{time constant or rise time})$$

ii) We inspected the effects of τ_{min} values by estimating the model of (10) corresponding to the process of (12) with n=5, m=4, θ=0.1, τ_{max}=5.0 and varioust τ_{min} values. The same as the τ_{max} case, Bode plots of the process and the models are nearly accorded. From the results and additionally extensive simulations, we can recognize that the proposed method provides a good model and shows an acceptable robustness for various τ_{min} and τ_{max} values.

iii) To inspect the effects of the time delay, we estimated the model parameters for θ=1.0, θ=2.0, θ=5.0 with $\tau_{min}=\theta$ and τ_{max} =20 as shown in Fig. 2. The proposed method provides very good models for the various time delay. From the results, we can recognize that the model of (10) with n=5 and m=4 can incorporate the large time delay process.

2. Identification Results for the Process Order and Position of Poles and Zeroes

i) Consider the following fifth order plus time delay process

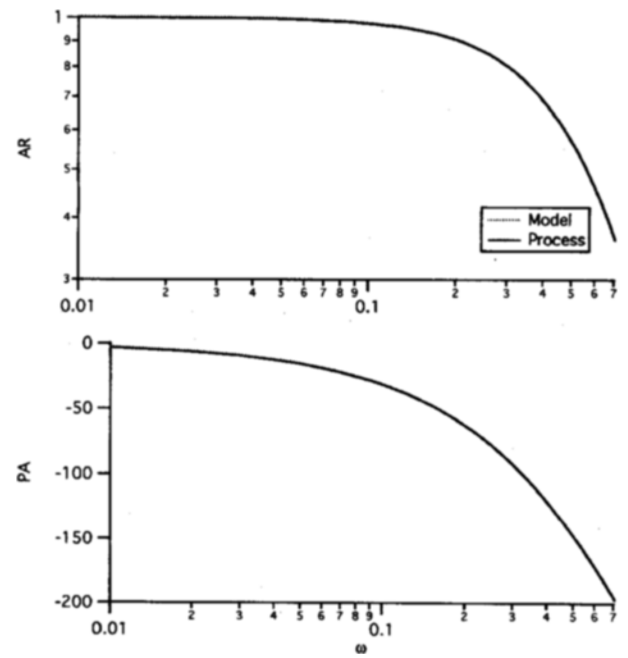

Fig. 3. Bode plots of the process and the model for the high order process.

$$G_p(s) = \frac{\exp(-0.5s)}{(s+1)^5} \tag{14}$$

and Bode plots of the estimated model in Fig. 3. Here, we used τ_{min}=0.5, τ_{max}=5, n=5 and m=4. The method provides almost the same frequency data as those of the fifth order plus time delay process. Additionally, we simulated many fifth order plus time delay processes whose poles are differently located in the left-half plane. From the results, we conclude that the model of (10) with n=5 and m=4 can treat the high order plus time delay process.

ii) Consider the following second order plus time delay model

$$G_p(s) = \frac{\exp(-0.1s)}{s^2+2\xi s+1} \tag{15}$$

and Bode plots of the process and the estimated model for ξ =0.3 and ξ=3.0 with τ_{min}=0.1, τ_{max}=5, n=5 and m=4 are shown in Fig. 4. Both the underdamped and the overdamped process can be efficiently treated by the proposed method.

iii) Consider the following nonminimum phase zero and time delay process

$$G_p(s) = \frac{\exp(-0.1s)(1-3.0s)}{s^2+2s+1} \tag{16}$$

and the estimated process model in Fig. 5. We can recognize that the proposed identification strategy still provides a good model for the nonminimum phase zero on the basis of the results and additional several examples of multiple nonminimum and minimum phase zeroes processes.

In summary, we can recognize from many numerical examples that the proposed method may well approximate various types of the process such as high order, underdamped and overdamed, large time delay, minimum phase zero and nonminimum phase zero processes.

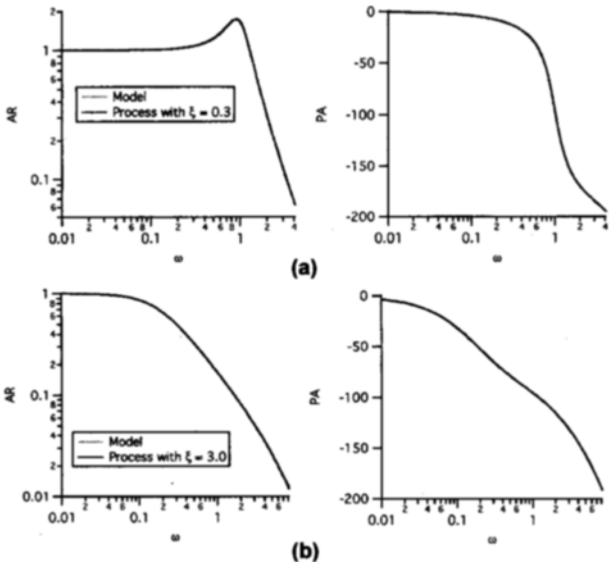

Fig. 4. Bode plots of the process and the model for the underdamped process and the overdamped process.

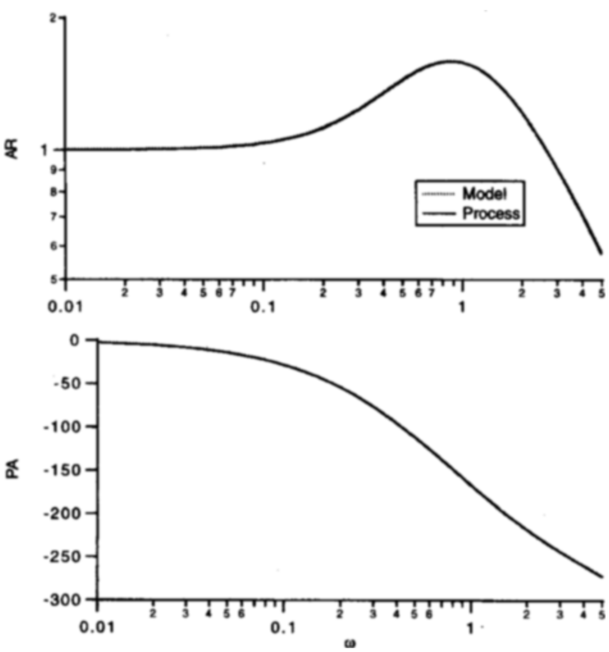

Fig. 5. Bode plots of the process and the model for the nonminimum phase zero process.

MODEL REDUCTION AND ON-LINE TUNING METHOD

Usually, tuning relations for the tuning of the PID controller such as Cohen-Coon, Integral of the Time-weighted Absolute value of the Error (ITAE), Internal Model Control (IMC) are based on the first order plus time delay or second order plus time delay model. Even though the Zeigler-Nichols (ZN) tuning rule can be applied to a high order plus time delay model, it frequently shows poor performances especially for the large time delay and underdamped process. Therefore, if the given model is a high order plus time delay model, it should be reduced to low order plus time delay model to tune the PID controller more efficiently. Here, the model $G_m(s)$ is a high order plus time delay model so that it should be reduced.

From (10), we can obtain the reduced second order plus time delay model easily using the following equations. Assume the reduced second order plus time delay model is as follows

$$G_{r-m}(s)=\frac{k_m\exp(-\theta_m s)}{\tau_m^2 s^2+2\tau_m\xi_m s+1} \qquad (17)$$

Then the static gain of the reduced model is obtained by (18)

$$k_m = G_m(0) \qquad (18)$$

and ξ_m and τ_m are estimated to satisfy (19)

$$|G_m(j\omega)| \approx |G_{r-m}(j\omega)| = \left|\frac{k_m\exp(-j\theta_m\omega)}{1-\tau_m^2\omega^2+j2\tau_m\xi_m\omega}\right| = \frac{k_m}{\sqrt{\{1-\tau_m^2\omega^2\}^2+\{2\tau_m\xi_m\omega\}^2}} \qquad (19)$$

By using an off-line (batch) least squares method, ξ_m and τ_m satisfying (19) as much as possible can be directly estimated from (20) and (21) [Levy, 1959]

$$\tau_m^4|G_m(j\omega_i)|^2\omega_i^4+(4\tau_m^2\xi_m^2-2\tau_m^2)\omega_i^2|G_m(j\omega_i)|^2 = k_m^2-|G_m(j\omega_i)|^2 \qquad (20)$$

$$0<\omega_0<\omega_1<---<\omega_i<---\le\omega_u \qquad (21)$$

and additionally the following phase lag equation for the second order plus time delay model is used to estimate the time delay of the reduced model.

$$\theta_m=\frac{\pi+\arctan 2(-2\tau_m\xi_m\omega_u,\ 1-\tau_m^2\omega_u^2)}{\omega_u} \qquad (22)$$

Here, subscript r-m and m denote 'reduced-model' and 'model', respectively. ω_u represents the ultimate frequency of the proceess model $G_m(s)$ and ω_i's are located with equal interval between 0 and ω_u. Here, ω_u can be calculated by finding the root of $Im(G_m(j\omega))=0$. We consider the frequency below ω_u in (20) and (22) because the controller may work in this frequency region. (20) is the same approach as the Levy's [1959] method. Though the improved methods [Sanathanan and Koerner, 1963; Payne, 1970; Whitfield, 1986] can be used, we use the Levy's [1959] method for simplicity. (22) can be easily derived from the phase lag equation of the second order plus time delay process.

The same procedure can be done to obtain the reduced first order plus time delay model. Therefore, if we want to use some kinds of tuning rules based on the first order plus time delay model such as ITAE, IMC, Cohen-Coon tuning methods, we should reduce (10) to the first order plus time delay model. On the other hand, if we want to use the second order plus time delay model and the corresponding tuning rule such as Sung et al.'s [1996] tuning method, we can use (17), (20) and (22). Sung et al.'s [1996] tuning rule is shown in Table 1.

Here, it should be emphasized that the first order plus time delay model can't well approximate an underdamped process or a high order process whose poles are concentrated on one point. In this case, the second order plus time delay model is strongly recommended in the viewpoint of accuracy. Here,

Table 1. PID tuning rule for the second order plus time delay model

Set point chang:

$$k_m k_c = -0.04 + \left\{0.333 + 0.949\left(\frac{\theta_m}{\tau_m}\right)^{-0.983}\right\}\xi_m,\ \xi_m \le 0.9$$

$$k_m k_c = -0.544 + 0.308\left(\frac{\theta_m}{\tau_m}\right) + 1.408\left(\frac{\theta_m}{\tau_m}\right)^{-0.832}\xi_m,\ \xi_m > 0.9$$

$$\frac{\tau_i}{\tau_m} = \left\{2.055 + 0.072\left(\frac{\theta_m}{\tau_m}\right)\right\}\xi_m,\ \frac{\theta_m}{\tau_m} \le 1$$

$$\frac{\tau_i}{\tau_m} = \left\{1.768 + 0.329\left(\frac{\theta_m}{\tau_m}\right)\right\}\xi_m,\ \frac{\theta_m}{\tau_m} > 1$$

$$\frac{\tau_m}{\tau_d} = \left\{1. - \exp\left(-\frac{\left(\frac{\theta_m}{\tau_m}\right)^{1.060}\xi_m}{0.870}\right)\right\}\left\{0.55 + 1.683\left(\frac{\theta_m}{\tau_m}\right)^{-1.090}\right\}$$

Disturbance rejection:

$$k_m k_c = -0.67 + 0.297\left(\frac{\theta_m}{\tau_m}\right)^{-2.001} + 2.189\left(\frac{\theta_m}{\tau_m}\right)^{-0.766}\xi_m,\quad \frac{\theta_m}{\tau_m} < 0.9$$

$$k_m k_c = -0.365 + 0.260\left(\frac{\theta_m}{\tau_m} + 1.4\right)^2 + 2.189\left(\frac{\theta_m}{\tau_m}\right)^{-0.766}\xi_m,\quad \frac{\theta_m}{\tau_m} \ge 0.9$$

$$\frac{\tau_i}{\tau_m} = 2.212\left(\frac{\theta_m}{\tau_m}\right)^{0.520} - 0.3,\ \frac{\theta_m}{\tau_m} < 0.4$$

$$\frac{\tau_i}{\tau_m} = -0.975 + 0.910\left(\frac{\theta_m}{\tau_m} - 1.845\right)^2 + \left\{1 - \exp\left(-\frac{\xi_m}{0.15 + 0.33\left(\frac{\theta_m}{\tau_m}\right)}\right)\right\}\left\{5.25 - 0.88\left(\frac{\theta_m}{\tau_m} - 2.8\right)^2\right\},\ \frac{\theta_m}{\tau_m} \ge 0.4$$

$$\frac{\tau_m}{\tau_d} = -1.9 + 1.576\left(\frac{\theta_m}{\tau_m}\right)^{-0.530}\left\{1 - \exp\left(-\frac{\xi_m}{-0.15 + 0.939\left(\frac{\theta_m}{\tau_m}\right)^{-1.121}}\right)\right\}\left\{1.45 + 0.969\left(\frac{\theta_m}{\tau_m}\right)^{-1.171}\right\}$$

Sung et al.'s [1996] tuning rule can be applied to $0.0 \le \theta_m/\tau_m \le 2.0$. Therefore, even though the proposed identification method can identify a very large time delay process as shown in the previous section, the proposed autotuning method can be applied to the process within $0.0 \le \theta_m/\tau_m \le 2.0$. However, the process including the time delay larger than the dominant time constant is very rare.

If predictive control strategies such as DMC or MAC are used, the step response or impulse response can be estimated from (10). The proposed method uses the least squares technique considering all measured data sets and it is well-known fact that it provides unbiased estimation results for white measurement noises and good smoothing performance for various measurement noises and high frequency disturbances. Contrarily, in the open loop step test, the step response or impulse response for the predictive control strategy is obtained by measuring directly without any smoothing. Therefore, it is obvious that the proposed method is more robust to measurement noises and high frequency disturbances than the open loop step test. Also, the step test requires a long identification time because it can be over at the steady state, but the proposed method can be complete within shorter time because it is not necessary to wait the steady state. Moreover, it can confine the process output within a desired region more easily.

SIMULATION STUDY

To show the performances of the proposed identification method for the PID controller autotuning, consider the following examples.

(i) Third order plus time delay process controlled by the ideal PID controller without measurement noise

$$G(s) = \frac{\exp(-0.2s)}{(s+1)^3} \tag{23}$$

Table 2 shows the ideal PID controller gains during the identification work and the identified models ($G_{r\text{-}m}(s)$). Bode plots of the process G(s), the model $G_m(s)$ and the reduced model $G_{r\text{-}m}(s)$ are shown in Fig. 6. Fig. 7 compares the control performance of the proposed method using Sung et al.'s [1996] tuning method with that of the continuous cycling method with Zeigler-Nichols tuning rule. From the simulation results, we recognize that the proposed method provides good model parameters.

(ii) process (i) corrupted with an uniformly distributed measurement random noise between −0.3 and 0.3.

Here, the set point-to-noise ratio is 1 : 0.6. This is very large

Table 2. Obtained model and reduced model

Reduced model for process (i): $G_{r-m}(s) = \dfrac{\exp(-0.594s)}{2.199^2 s^2 + 2.610s + 1}$
$\tau_{min} = 0.25,\ \tau_{max} = 20,\ n = 5,\ m = 4$
PID controller during identification work for process (i) and (ii): $G_c(s) = 1.0\left(1 + \dfrac{1}{7s} + 1.5s\right)$

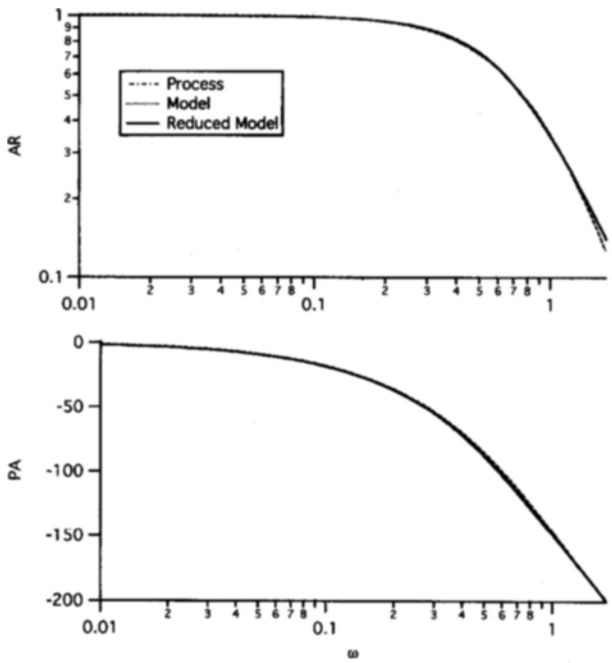

Fig. 6. Bode plots of the reduced model, the model and the process.

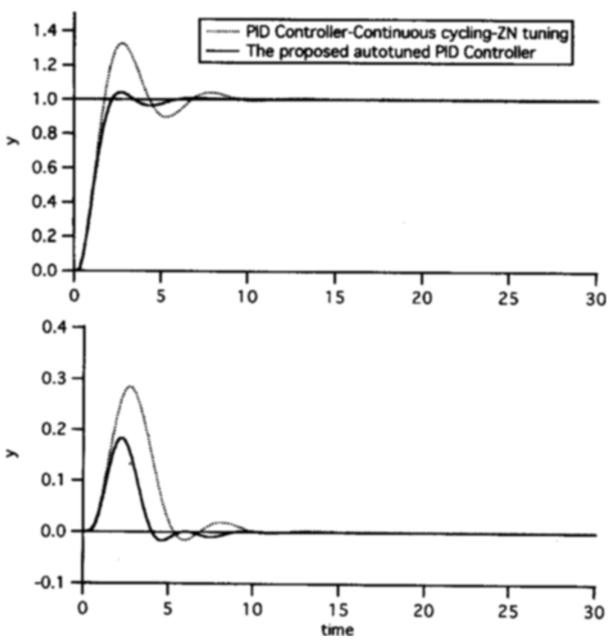

Fig. 7. Control results of the proposed autotuned PID controller.

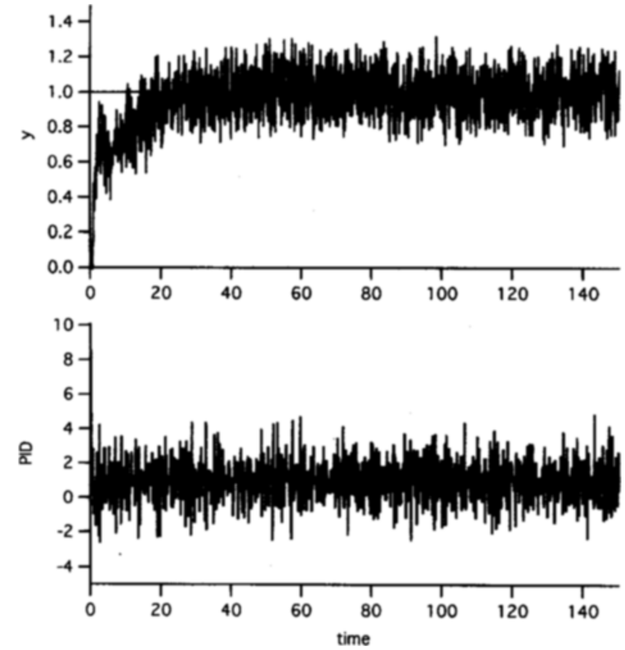

Fig. 8. Responses of the ideal PID controller and the process during the identification work when the measured output is corrupted by random noise.

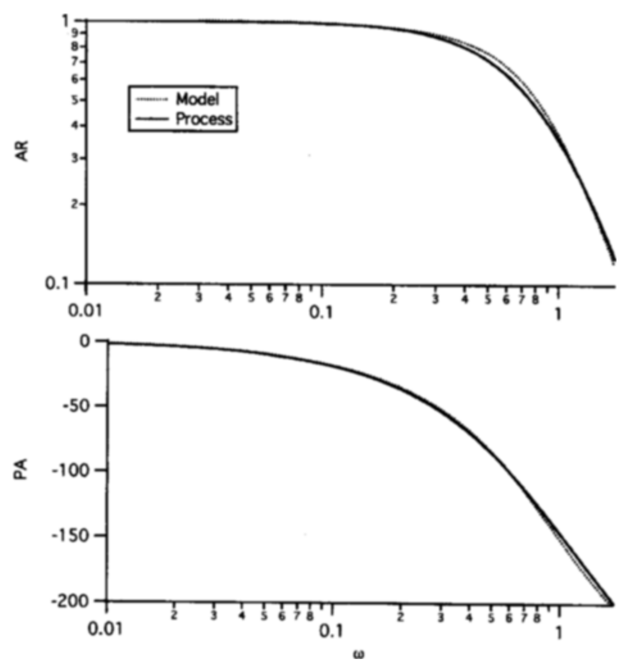

Fig. 9. Bode plots of the process and the model when the measured output is corrupted by random noise.

value compared with that of practical control problems. The process and the ideal PID controller responses during the identification work are shown in Fig. 8 and Table 2. Here, the sampling time of the PID controller is chosen by 0.2 to prevent infinite control action. In Fig. 8, the fast fluctuation of the control action is due to the derivative term of the PID controller. Previous methods using several dominant data points without a smoothing function can't be applied to identify the process because of severe measurement noises. Nevertheless, the identified model by the proposed method shows a good accuracy as shown in Fig. 9. We guess that the robustness to measurement noises is due to the integral action such as (4) and (5) and the least squares estimation.

iii) Consider the following 3 identical tank series [Rough, 1987]

$$\frac{dh_1}{dt} = -2\sqrt{h_1} + 2u \qquad (24)$$

$$\frac{dh_2}{dt} = -2\sqrt{h_2} + 2\sqrt{h_1} \qquad (25)$$

$$\frac{dh_3}{dt} = -2\sqrt{h_3} + 2\sqrt{h_2} \qquad (26)$$

Here, the level of the third tank (process output) is controlled by adjusting the influent flowrate (controller output). This process shows a nonlinearity for the different operating region. Through the linearization at the reference value h_{ref}, the following linearized process can be obtained.

$$\sqrt{h_{ref}}\frac{d(h_1 - h_{ref})}{dt} = -(h_1 - h_{ref}) + 2\sqrt{h_{ref}}(u - u_{ref}) \qquad (27)$$

$$\sqrt{h_{ref}}\frac{d(h_2 - h_{ref})}{dt} = -(h_2 - h_{ref}) + (h_1 - h_{ref}) \qquad (28)$$

$$\sqrt{h_{ref}}\frac{d(h_3 - h_{ref})}{dt} = -(h_3 - h_{ref}) + (h_2 - h_{ref}) \qquad (29)$$

$$G_p(s) = \frac{2\sqrt{h_{ref}}}{(\sqrt{h_{ref}}\,s + 1)^3} \qquad (30)$$

We use the anti-derivative kick PID controller with the step set point change from 50 to 51 to activate the process and Fig. 10 shows Bode plots of the estimated model and the linearized process at the reference value 50. Here, we used τ_{min}=1.0, τ_{max}=6, n=5 and m=3. The proposed identification method provides a good model for the narrow operating region in the nonlinear system.

Fig. 11 shows Bode plots of the linearized process and the identified model when the static input disturbance corresponding to the process output of the magnitude 0.15 (15 % of the set point change) is entered at the starting point. The proposed method provides an acceptable model even though the disturbance is entered during the identification work. In many simulation studies, we can recognize that it provides an acceptable robustness to static disturbances or sinusoidal disturbances. Here, it should be noted that as the magnitude of the activation increases, the robustness to disturbances and noises can be enhanced, on the other hand the effects of the nonlinearity of the process can increase and a large deviation of the process output would be undesirable.

Fig. 12 shows the activated process output by the anti-derivative kick PID controller with a wide step set point change

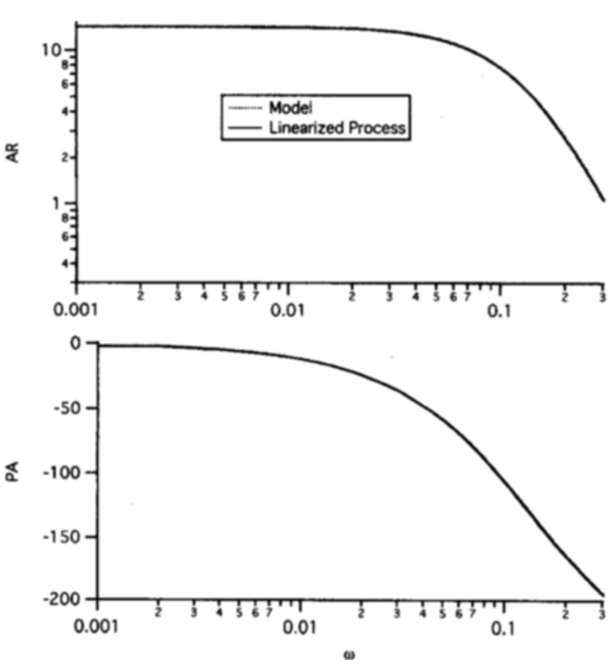

Fig. 10. Bode plots of the model and the linearized process.

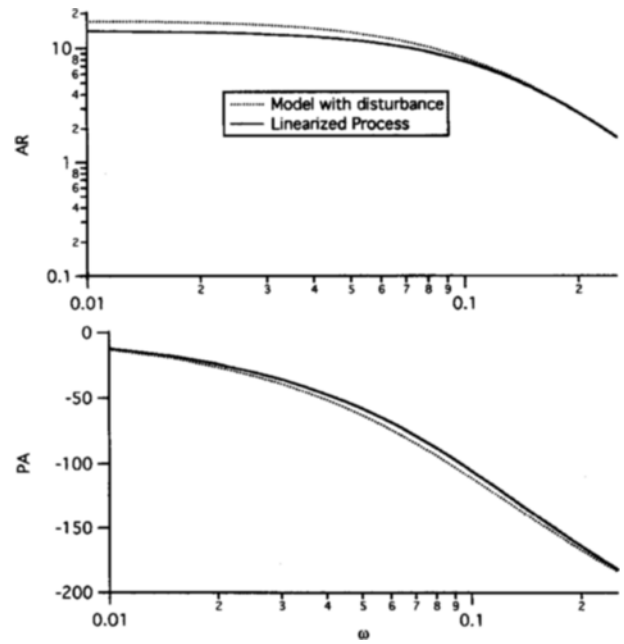

Fig. 11. Bode plots of the model and the linearized process when disturbance enters during the identification work.

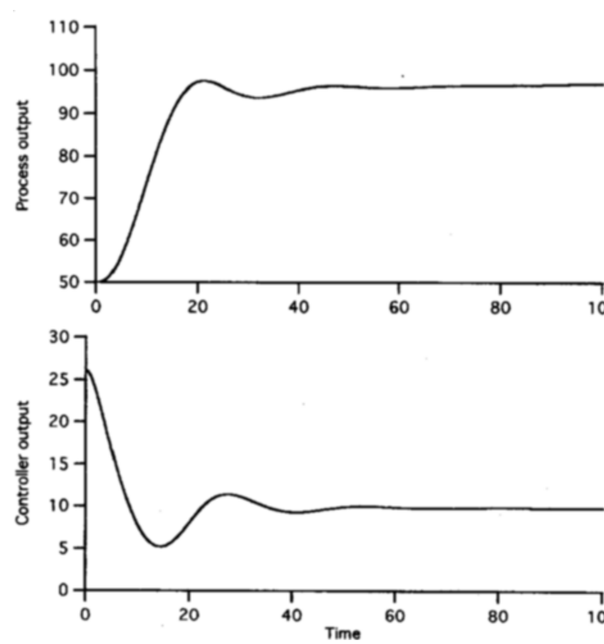

Fig. 12. Responses of the anti-derivative kick PID controller and the process during the identification work for the tank series process with the set point change from 50 to 100.

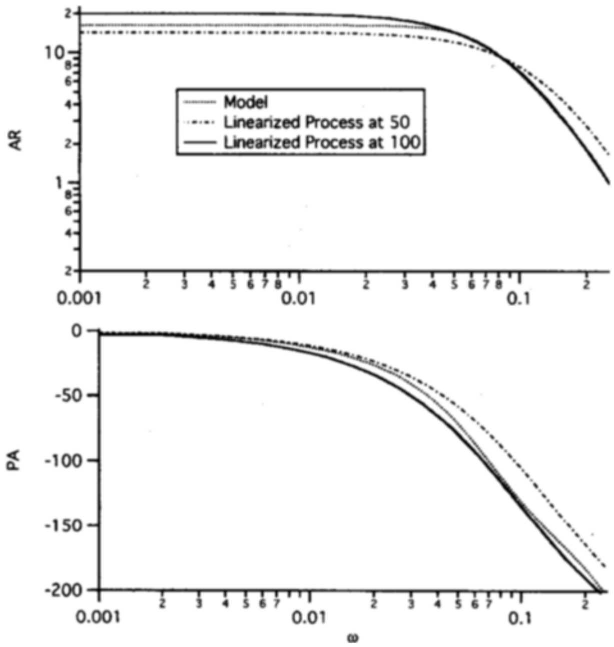

Fig. 13. Bode plots of the model and the linearized process.

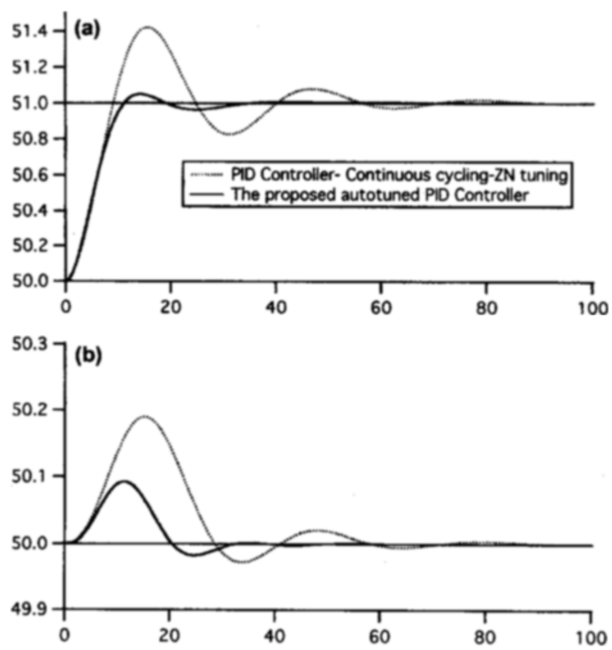

Fig. 14. Control results of the proposed autotuned PID controller.

from 50 to 100 to introduce a large nonlinearity and Fig. 13 shows Bode plots of the linearized processes at the reference value 50 and 100 and the identified model. Here, we used τ_{min} =1.0, τ_{max}=5.0, n=5 and m=4. Since the identified model exists between the linearized model at h_{ref}=50 and that of h_{ref}=100, we can infer that the identified model by the proposed identification is acceptable for the nonlinear system including wide operating region.

As shown in Fig. 14, the proposed autotuned PID controller based on the second order plus time delay model shows a good control performance for the step set point change from 50 to

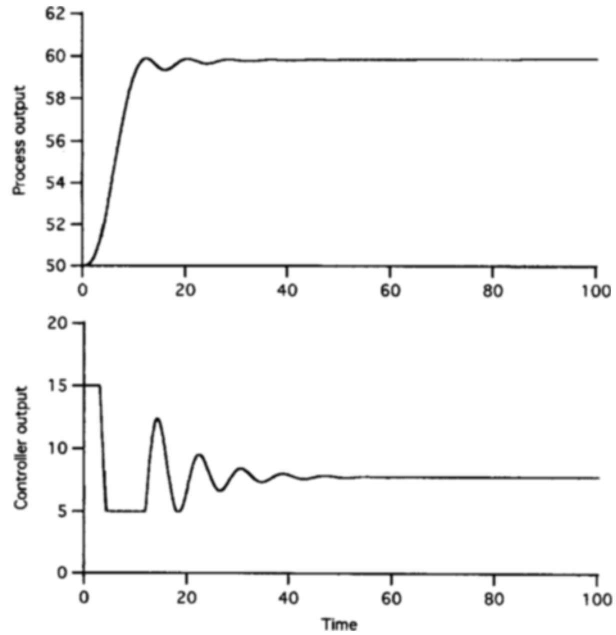

Fig. 15. Responses of the anti-derivative kick PID controller and the process during the identification work for the tank series process with the valve saturation.

100. Here, the proposed autotuned PID controller is tuned based on the Sung et al. [1996]'s tuning method and the identified model from the test signal and the process output in Fig. 10.

Fig. 15 shows the activated process output by the anti-derivative PID controller with the set point change from 50 to 60. It should be noted that the controller output are confined within u_{max}=15.0 and u_{min}=5.0. That is, the valve saturation produces the nonlinearity so that many previous on-line closed-loop identification methods such as relay feedback methods or P controller methods may be fail because they uses structural information. However, the proposed method can incorporate the nonlinearities resulted from the valve saturation or the manual mode operation during the identification work because it requires only process input and process output data sets rather than structural information. As shown in Fig. 16, the identification performance does not affected by the nonlinearities of the valve saturation.

Based on the many simulation examples, we can conclude that the proposed identification method may incorporate the nonlinear process, actuator saturation or manual mode operation, measurement noise and the small disturbance during the identification work.

EXPERIMENT STUDY

We applied the proposed method to control the level of tanks. As shown in Fig. 17, the process output and input are the level of the lowest tank and the control signal to manipulate the value, respectively. We used the AD/DA converter using RS232C serial communication to acquire the process data from DP cell and send the control signal to the valve. The obtained model is as follows.

$$G_m(s)=\frac{4.63\exp(-(263.21\mathrm{sec})s)}{(224.04\mathrm{sec})^2s^2+2\times(224.04\mathrm{sec})\times1.45s+1} \tag{31}$$

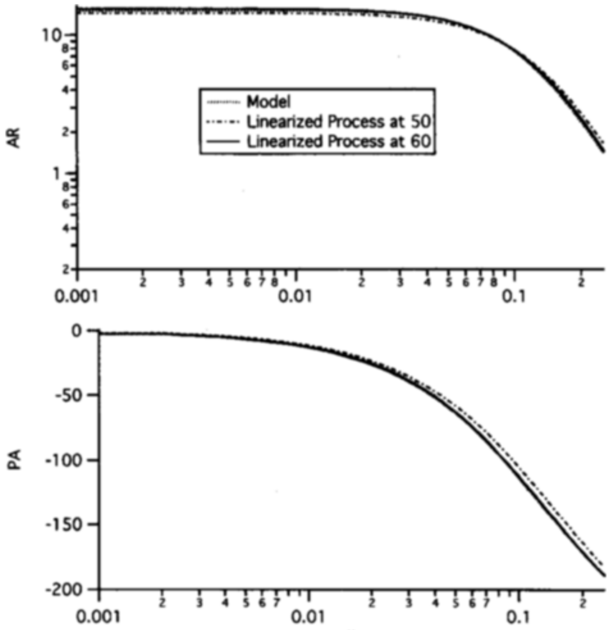

Fig. 16. Bode plots of the model and the linearized process.

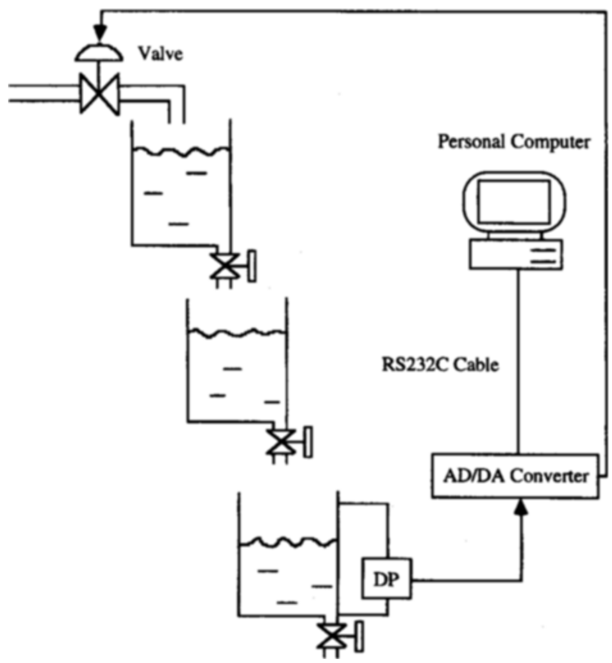

Fig. 17. Tank process for the experimental test of the proposed method.

Experimental results are shown in Fig. 18. Two step set changes are done after the autotuning work is over. The control performance of the initial PID controller is bad, however after the automatic tuning of the PID controller based on the previously obtained data sets and Sung et al. [1996]'s tuning method, it shows the good set point tracking performance. From the results of the experiment, we can recognize that the proposed method shows a good control performance and can be applied in industry.

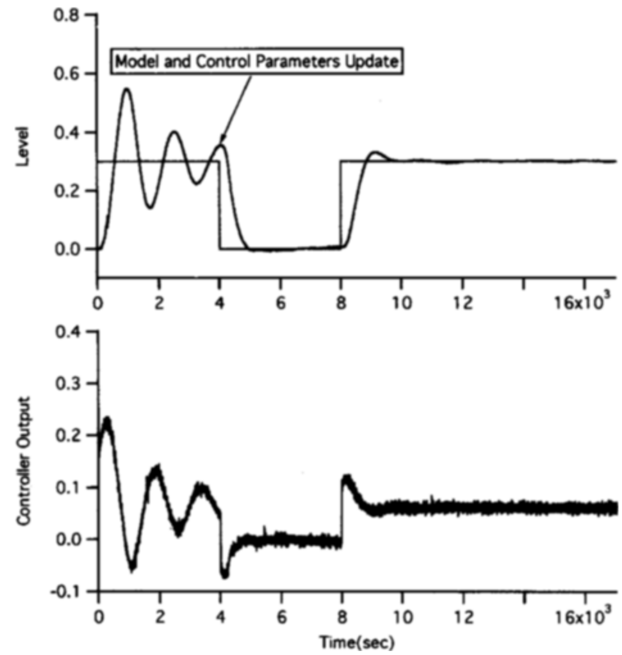

Fig. 18. Control results of the proposed method in controlling the level of the pilot-scaled tank.

CONCLUSIONS

We proposed a new on-line identification method for the automatic tuning of the PID controller to overcome disadvantages of previous identification methods. The proposed method doesn't require a special test signal generator such as relay or a P controller that is, can utilize arbitrary test signal generator such as the controller itself, P controller, relay, pulse signal or step signal generator. It shows a good model accuracy and robustness to the measurement noise, the large time delay process, the high order process, the mild nonlinear process. The proposed method needs only the measured process output and the calculated controller output so it can incorporate the nonlinearities resulted from actuator saturation or manual mode operation. Because it uses a numerical integral technique, the sampling time should be small during the identification work. The proposed autotunner combined with the identification method and the PID tuning rule using the model reduction method shows better control performances than previous autotuning methods. Finally, the proposed identification method can be applied to obtain the model for other types of controllers such as DMC or MAC etc.

ACKNOWLEDGEMENT

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NOMENCLATURE

d : vector composed of the coefficients of the denominator of model transfer function

G(s) : process transfer function
$G_m(s)$: model transfer function
$G_{r\text{-}m}(s)$: reduced model transfer function
h : level
h_{ref} : reference value for linearization
k : static gain of the process
n : vector composed of the coefficients of the numerator of transfer function
n_s : the number of s_i
s_i, s : variable of Laplace transform
t : time
Δt : sampling time
u(s) : Laplace transform of the controller output
u(t) : controller output
u_{min} : minimum value of the controller output
u_{max} : maximum value of the controller output
y(s) : Laplace transform of the process output
y(t) : process output

Greek Letters

θ : time delay
$\theta_{eqivalent}$: equivalent time delay
ω : frequency
ω_u : ultimate frequency
ξ : damping factor
τ : time constant
τ_{min}, τ_{max} : time to determine the maximum and minimum s_i values

Subscripts

m : model, the number of denominator coefficients of transfer function
n : the number of numerator coefficients of transfer function
p : process
r-m : reduced model

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