DESIGN OF ON-LINE AUTO-TUNING PID CONTROLLER FOR POWER PLANT PROCESS CONTROL

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Abstract: In the power plant process control, classical PID controllers are widely used. In order to get the desired control performances, the correct tuning of PID controllers is very important. In this paper, a new auto-tuning method of PID controller without using test signal generator has been developed. This method uses only the measured process output and controller output signals to identify the unknown control process. From the estimated process model, a controller design rule is derived such that it minimizes the average mean squared error between desired closed-loop step response and that of the control system. Because it is possible to estimate the process without using any special test signal generator, this method can be applied to the safety-related processes such as nuclear power plant control system.

1. Introduction

The Proportional-Integral-Derivative (PID) controller has been widely used in the power plant process control, since its structure is simple and familiar to the field engineer [1]. While the plant is in initial startup or when the process system status has been changed significantly by system upgrade or modification, it is necessary to tune the controller to find the optimal PID parameters. The methods to determine the optimal PID parameters automatically have been studied for long time for reliable and simple tuning of controllers, and some of them were successful and commercialized [2]. One of the methods which was successfully applied in the industry processes is relay feedback controller [3, 4]. This method uses relay feedback to identify unknown process, and Ziegler-Nichols tuning formula to find tuning parameters from the identified process information [5]. Because this method uses a test signal generator that is relay feedback to find ultimate gain and frequency, this may be harm to the stable process operation. Therefore, using this kind of tuning method in the safety-related processes such as nuclear power plant control system is not desirable.

A new auto-tuning method without using test signal generator has been developed in this paper. This method does not require any special test signal for process identification. It uses only the measured process output and controller output to identify the unknown control process. The ARMA model is used to identify the unknown control process from the process output and controller output signals measured for a given time period. From the estimated process model, a controller design rule is derived such that it minimizes the average mean squared error between desired closed-loop step response and that of the control system. Because it is possible to estimate the process without using any special test signal generator, this method can be applied to the safety-related processes such as nuclear power plant control system.

The developed method was extensively tested for various processes by computer simulation. It was successfully applied to the tuning of complex processes such as large time delay process, high order process, and mild nonlinear process. The test results were compared with the control performance of Zigler-Nichols tuning method. The results showed that the control performance of developed method was better than that of Ziegler-Nichols tuning method.

2. Auto-Tuning Method

The block diagram of a process control system and its tuning method are shown in Figure 1. The auto-tuning method proposed in this paper uses the measured process output $y(t)$ and controller output $u(t)$ to identify unknown control process. The identified process model is processed to determine the optimal PID controller parameters to meet the desired control performance criteria.

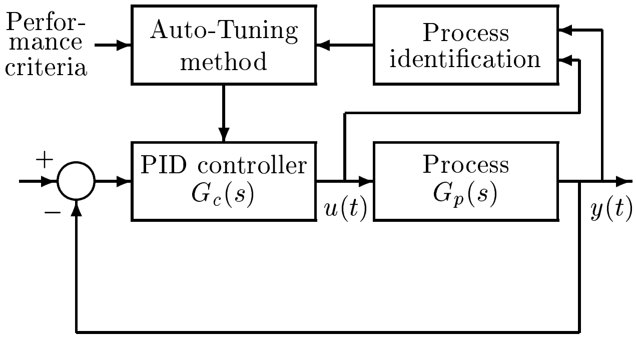


Figure 1. Block diagram of process control system

2.1 Process model

The continuous-time transfer function $G_p(s)$ of the unknown control process with arbitrary delay time can be expressed in the discrete-time model as

$$G_p(z^{-1}) = \frac{b_1 z^{-1} + b_2 z^{-2} + \cdots + b_n z^{-n}}{1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_n z^{-n}}. \quad (1)$$

The control process is modeled as n-th order ARMA (Auto-Regressive Moving Average) model, and the model coefficients, $(a_i, b_i, i = 1, 2, \cdots, n)$, are chosen to minimize the average mean squared error between measured process output $y(k)$ and model difference equation $y_M(k)$ over an appropriate time interval. The objective function that should be minimized is

$$J_1 = \sum_{k=0}^{N-1} \{y(k) - y_M(k)\}^2, \quad (2)$$

where $y(k)$ is process output signal measured from the operating control system with sampling time of T_s, and $y_M(k)$ is the process model difference equation which satisfies the following difference equation.

$$\begin{aligned} y_M(k) = {} & b_1 u(k-1) + b_2 u(k-2) + \cdots \\ & + b_n u(k-n) - a_1 y_M(k-1) \\ & - a_2 y_M(k-2) - \cdots - a_n y_M(k-n) \end{aligned} \quad (3)$$

The nonlinear least squares function J_1 was solved by Levenberg-Marquardt algorithm to find the model coefficients [6].

2.2 Controller model

Consider the transfer function of continuous-time PID controller:

$$G_c(s) = K_p \left[1 + \frac{1}{T_i s} + T_d s\right] \quad (4)$$

This controller is characterized by three tuning parameters, K_p, T_i and T_d, and they specify proportional gain, integral time and derivative time respectively.

The discretization method used to derive the discrete-time PID controller model is a simple backward difference approximation method. By approximating s by $(1 - z^{-1})/T_s$, the discrete-time transfer function $G_c(z^{-1})$ is obtained.

$$G_c(z^{-1}) = K_p \left[1 + \frac{T_s}{T_i}\frac{1}{1 - z^{-1}} + \frac{T_d}{T_s}(1 - z^{-1})\right] \quad (5)$$

From equations (1) and (5), the closed-loop transfer function of this control system can be written as

$$H(z^{-1}) = \frac{G_c(z^{-1}) G_p(z^{-1})}{1 + G_c(z^{-1}) G_p(z^{-1})}. \quad (6)$$

2.3 Performance criteria

If we assume that the desired closed-loop transfer function is

$$H_d(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \quad (7)$$

where ω_n denotes natural frequency and ζ denotes damping factor. From equation (7), the desired closed-loop step response can be solved analytically as [7]

$$h_d(t) = 1 - \frac{e^{-\zeta\omega_n t}}{\sqrt{1-\zeta^2}} \sin\left(\omega_n \sqrt{1-\zeta^2} t - \phi\right), \quad (8)$$

where

$$\phi = \tan^{-1} \frac{\sqrt{1-\zeta^2}}{-\zeta}.$$

By assigning appropriate values to the natural frequency and damping factor in equation (8), we can obtain a system having desired rise time and overshoot.

2.4 Tuning parameters

The optimal PID parameters are determined such that the average mean squared error between the closed-loop step response of the control process and the desired closed-loop step response $h_d(k)$ is minimized. Then, the performance index is expressed as

$$J_2 = \sum_{k=0}^{N-1} \{h_d(k) - h(k)\}^2, \quad (9)$$

where $h(k)$ is the closed-loop step response of the process control system which can be detremined by solving equation (6).

The necessary condition to minimize the performance index J_2 is $\nabla J_2(K_p, T_i, T_d) = 0$, i.e.,

$$\begin{aligned} \sum_{k=0}^{N-1} \{h_d(k) - h(k)\} \frac{\partial h(k)}{\partial K_p} &= 0 \\ \sum_{k=0}^{N-1} \{h_d(k) - h(k)\} \frac{\partial h(k)}{\partial T_i} &= 0 \\ \sum_{k=0}^{N-1} \{h_d(k) - h(k)\} \frac{\partial h(k)}{\partial T_d} &= 0. \end{aligned} \quad (10)$$

The optimal PID parameters K_p, T_i and T_d were found by solving nonlinear least squares problem (9) and (10) using Levenberg-Marquardt algorithm.

3. Simulation

The auto-tuning method described in this paper has been implemented in software and tested by computer simulation. The following two process models were chosen for testing the proposed auto-tuning method.

$$G_1(s) = \frac{e^{-0.1s}}{s^2+2s+1} \quad (11)$$

$$G_2(s) = \frac{e^{-0.2s}}{(s+1)^3} \quad (12)$$

The selected process models are second and third order models with different delay time.

First, we assumed that the selected processes were being controlled by the PID controller which was tuned by relay feedback Ziegler-Nichols method. The PID parameters calculated by Ziegler-Nichols method are given in Table 1. Figure 2 shows the step responses of these processes controlled by the tuning parameters of Ziegler-Nichols method. The process output $y(k)$ and controller output $u(k)$ were measured with a sampling time of 0.1 second. The process ARMA models were estimated by fitting these measured signals to the model difference equations (3) by least squares method. An optimization utility in the MATLAB which implements a Levenberg-Marquardt algorithm was used for this purpose [8]. Various ARMA model orders were tested to investigate the modeling accuracy. It was found that the higher than third order models did not give much improvement in modeling accuracy than the third order model.

Table 1. PID parameters by Ziegler-Nichols method

	K_p	T_i	T_d
$G_1(s)$	10.914	0.800	0.192
$G_2(s)$	2.829	2.250	0.540

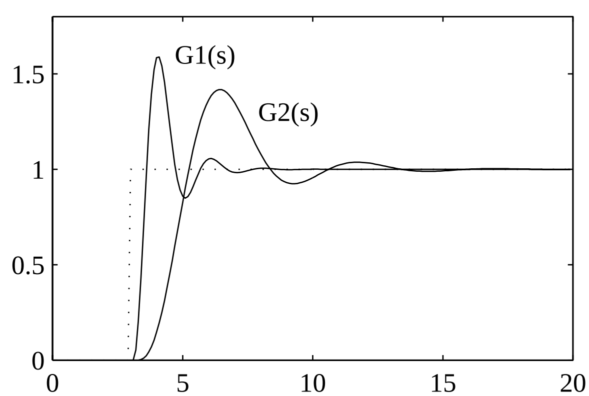


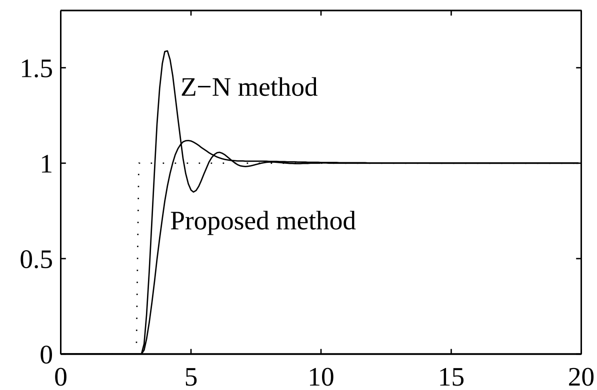
Figure 2. Step responses by Ziegler-Nichols method

So, We had selected third order model for both process models, $G_1(s)$ and $G_2(s)$. The estimated model coefficients, (a_1, a_2, a_3, b_1, b_2, b_3), were (-2.618, 2.283, -0.664, -0.002, 0.012, -0.008) and (-2.718, 2.464, -0.745, 0.000, -0.001, 0.002) for process models $G_1(s)$ and $G_2(s)$ respectively.

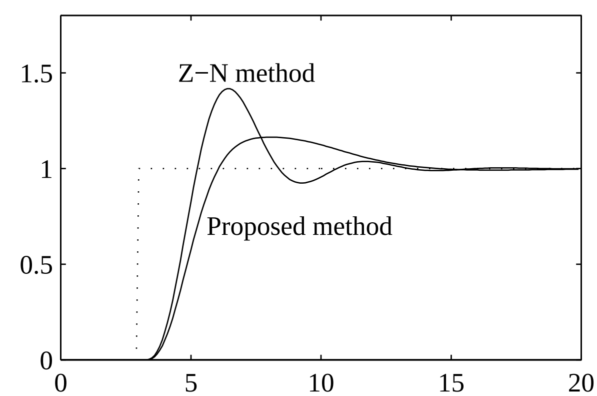
The proposed auto-tuning method was applied to these identified process models to find the optimal PID parameters by giving (ζ, ω_n) as control performance criteria. The performance criteria (ζ, ω_n) were given as (0.7, 3) and (0.8, 1.5) to processes $G_1(s)$ and $G_2(s)$ respectively. The Levenberg-Marquardt algorithm was used again to find the optimal PID parameters to match desired step responses $h_d(k)$ and closed-loop step responses of the processes $h(k)$ in the least squares sense. The optimal PID parameters calculated by proposed method are given in Table 2. The comparisons of the step responses by proposed method and relay feedback Ziegler-Nichols method are shown in Figure 3.

Table 2. PID parameters by proposed method

	K_p	T_i	T_d
$G_1(s)$	4.393	2.317	0.277
$G_2(s)$	2.001	2.263	1.076



(a) $G_1(s)$



(b) $G_2(s)$

Figure 3: Comparison of step responses of proposed and Ziegler-Nichols method

It is seen that the proposed method can achieve desired control performances by giving desired performance criteria (ζ, ω_n).

4. Conclusions

A new auto-tuning method of PID controller without using test signal generator has been developed, and tested by computer simulation. The main advantage of this method is that it is not using any test signal generator to identify unknown control process, and user can find optimal PID parameters by giving desired control performance criteria. Because it is possible to estimate the process without using any special test signal generator, this method can be applied to the safety-related process system such as nuclear power plant control system.

References

[1] F. G. Shinskey, "Process Control Systems : Application, Design, and Tuning", McGraw-Hill, 1988

[2] P. E. Wellstead and M. B. Zarrop, "Self-tuning Systems : Control and Signal Processing", John Wiley & Sons, 1991

[3] K. J. Åström and T. Häglund, "Automatic tuning of simple regulator with specifications on phase and amplitude margins", Automatica, Vol. 20, pp. 645-651, 1984

[4] K. J. Åström and T. Häglund, "Automatic tuning of PID Controllers", Instrument Society of America, 1988

[5] J. G. Ziegler and N. B. Nichols, "Optimum setting for automatic controllers", Trans. ASME, Vol. 65, pp. 433-444, 1943

[6] L. Ljung, "System Identification : Theory for the User", P T R Prentice-Hall, 1987

[7] B. C. Kuo, "Automatic Control Systems", Prentice-Hall, 1987

[8] A. Grace, "Optimization Toolbox for Use with MATLAB", The Mathworks Inc., 1994