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AUTO-TUNING OF CONTROL PARAMETERS FOR NUCLEAR PLANT PROCESS CONTROL

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ABSTRACT

An auto-tuning system for tuning PID control parameters automatically has been developed. The system is composed of a portable PC, a data acquisition part and application software that implements the auto-tuning algorithm. The portable auto-tuning system can be easily installed in the power plant field area, and it measures the process and controller output signals for appropriate time interval. From the measured data, the system identifies the unknown process and computes the optimal PID control parameters such that they minimize a performance index to acquire a desired control performance. Because it is possible to estimate the control processes without using any special test signal generator, the auto-tuning system can be used in the critical systems such as the control systems of nuclear power plants.

1. INTRODUCTION

The PID controller has been widely used in the various process industries, because it shows good control performance in spite of its simple structure when its control parameters are well tuned. The control parameters of PID controller need to be tuned in order to get the desired control performance, while the plant is in initial startup or when the process status has been changed significantly by system upgrade or modification. Typically, the control parameters are determined by the heuristic information obtained from the process operations. This approach requires a lot of time, efforts and expenses, and it is difficult to validate the control parameters, theoretically.

Since Ziegler and Nichols (1943) published the methods to determine PID parameters, methods to determine the optimal PID control parameters automatically have been studied for long time. Åström and Hägglund (1984, 1988) presented a method that gives process characteristic information using relay feedback. Melo and Fiedly (1992) developed an on-line process identification method, and Sung and Lee (1995) improved the existing method. Optimal PID control parameters can be determined from the identified process information using various methods such as Ziegler-Nichols formula, formula derived from the gain and phase margin analysis by Åström and Hägglund, and optimal parameter calculation formula using ISTE (Integral Squared Time Error) optimality by Zhuang and Atherton (1993). Although many auto-tuning methods were developed and commercialized until now, using them in the power plant processes is not desirable because they may causes unstable process operation.

This paper presents an auto-tuning system that can be applied to the auto-tuning of PID controllers in the nuclear power plants. The system does not require any special test signal for process identification. It uses only the measured controller and process output signals to identify the unknown control process. The ARMA (Auto-Regressive Moving Average) model is used to identify the unknown control process from the measured signals 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 process.

2. AUTO-TUNING SYSTEM

The auto-tuning system is composed of data acquisition hardware and application software which conducts auto-tuning procedures and analysis functions. The system hardware is equipped with a portable computer that controls data acquisition part and performs auto-tuning procedures, and a data acquisition part that measures controller and process output signals as shown in Fig. 1. The data acquisition part is designed with the National Instruments SCXI-1000 chassis and its data acquisition cards. An 8-channel analog input card and an 8-channel isolated signal conditioning card are used for multi-point data acquisition. Each process input and output signal is transmitted into the independent channel of data acquisition cards. The analog signals are converted to the digital data in the proper time interval and stored in the hard disk of the portable computer. The data acquired during the specific time period is analyzed and processed to calculate the optimal control parameters.

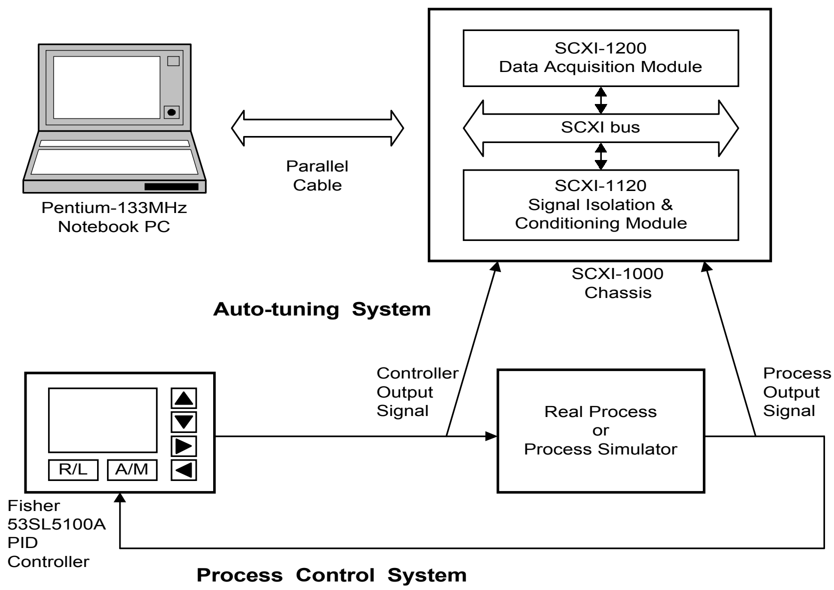


Fig. 1 Auto-tuning system hardware.

The system software was developed using Microsoft Visual Basic and National Instruments Component Works. It has four GUI modules: Initialization Module, Data Acquisition Module, Auto-tuning Module and Simulation Module. Initialization Module initializes the auto-tuning system and auto-tuning task. It sets task name, date and the configuration profile for data acquisition channels. Data Acquisition Module controls data acquisition devices, gathers data required in the auto-tuning algorithm. The acquired data are stored in the hard disk of portable computer. Auto-tuning Module performs the process model identification and optimal control parameter calculation. Simulation Module provides simulation functions by comparing the control performances of the old and the new parameters.

3. AUTO-TUNING ALGORITHM

The flow diagram of proposed auto-tuning algorithm is shown in Fig. 1. The auto-tuning algorithm proposed in this paper uses the measured process output signal $g(t)$ and controller output signal $u(t)$ to identify unknown control process. The identified process model is processed to determine the optimal control parameters to meet the desired control performance criteria.

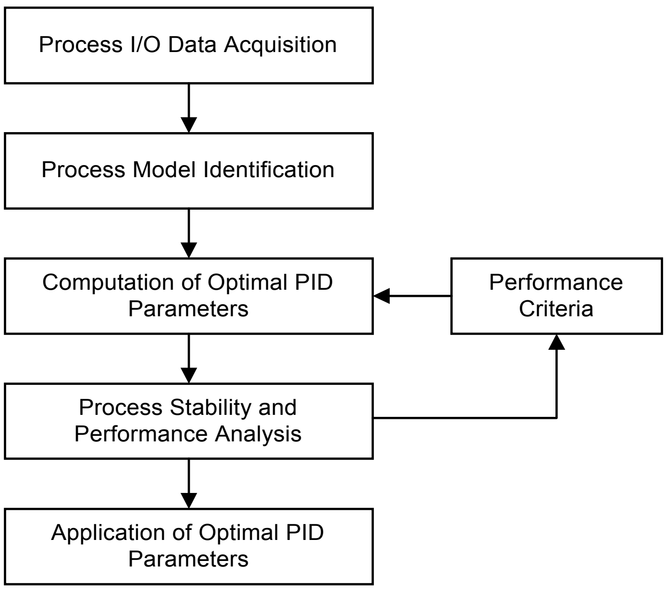


Fig. 2 The flow diagram of proposed auto-tuning algorithm.

3.1 Process Model

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

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

The control process is modeled as n-th order ARMA model, and the model coefficients, (a_i, b_i, i = 1, 2, … , n), are chosen to minimize the average mean squared error between measured process output $g(k)$ and model difference equation $g_p(k)$ over an appropriate time interval. The performance index that should be minimized is

$$J_1 = \sum_{k=0}^{N-1} \{g(k) - g_p(k)\}^2 , \tag{2}$$

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

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

3.2 Control System Model

The continuous transfer function of the PID controller is presented as follows.

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

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 transfer function $G_c(z^{-1})$ is obtained.

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

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

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

3.3 Determining PID Control Parameters

If we assume that the desired closed-loop transfer function is a second order system,

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

where ω_n denotes natural frequency and ξ denotes damping factor, then the desired closed-loop step response $h_d(k)$ can be obtained analytically. By assigning appropriate values to the natural frequency and damping factor in equation (7), we can obtain a system having desired rise time and overshoot.

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

$$J_2 = \sum_{k=0}^{N-1} \{h_d(k) - h(k)\}^2, \tag{8}$$

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

The necessary condition to minimize the performance index J_2 is

$$\nabla J_2(K_p, T_i, T_d) = 0. \tag{9}$$

The optimal PID parameters K_p, T_i and T_d can be determined by solving nonlinear least squares equation (9).

4. EXPERIEMENTS AND RESULTS

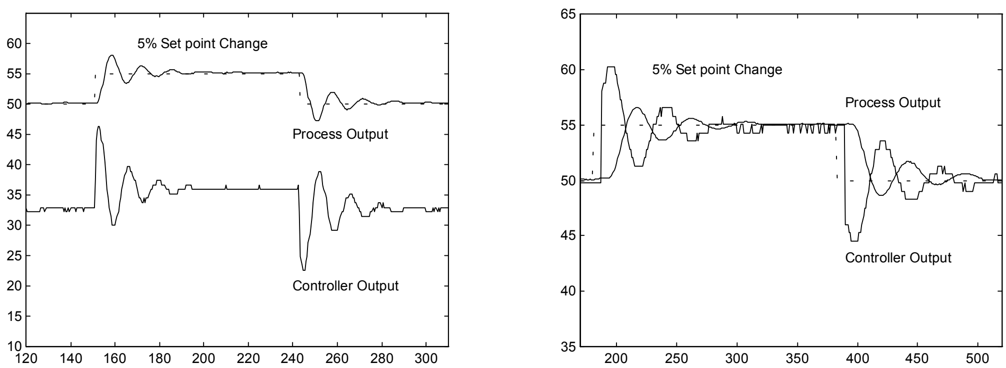
The auto-tuning system developed in this paper has been tested to verify its performances on the experiment setup as shown in Fig. 1. The plant process was simulated by PC to generate user specified process dynamics, and Fisher 53SL5100A PID controller was used to control the computer simulated process. The processes used in the simulation are as follows.

$$G_1(s) = \frac{1}{(3s+1)(5s+1)} e^{-0.5s} \tag{10}$$

$$G_2(s) = \frac{1}{(2s+1)(7s+1)(10s+1)} e^{-5s} \tag{11}$$

The first process model is chosen to simulate a process that has small delay time and fast response. The second process model is a process that has large delay time and slow response.

The processes were operated at the setpoint value of 50% until the signals are stabilized. After that, a 5% step change of setpoint was applied to initiate a transient response as shown in Fig. 3. The controller and process output signals were acquired during the process transient to identify the process models.



(a) Process 1 (b) Process 2

Fig. 3 Measured signals.

The coefficients of the ARMA model of the process were estimated from the measured signals. The coefficients of 2-nd and 3-rd order process models estimated by minimizing equation (2) iteratively until the performance index J_1 is less than 10^{-3}. The estimated coefficients of ARMA models for both process 1 and 2 were shown in Table 1, and the estimated delay time was 6 for process 2.

Table 1 Estimated process coefficients.

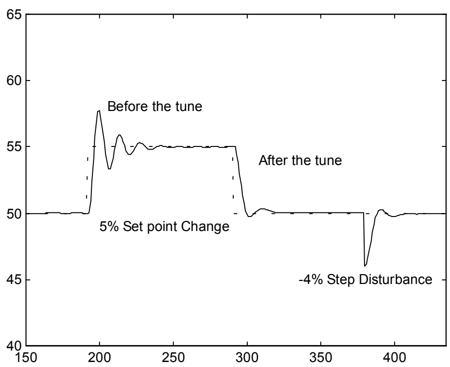
Coefficients	Process 1		Process 2	
	2-nd order	3-rd order	2-nd order	3-rd order
a_1	-1.7238e 0	-9.1759e-1	-1.7837e 0	-2.0734e 0
a_2	7.3962e-1	-6.4433e-1	7.9565e-1	1.3227e 0
a_3		5.9085e-1		-2.4006e-1
b_1	-1.7133e-2	-7.9955e-3	6.2685e-3	2.1821e-2
b_2	4.1359e-2	7.5491e-3	5.8585e-3	-2.9972e-2
b_3		4.4850e-2		1.7540e-2

The PID control parameters were determined from the estimated process models of Table 1 so that performance index J_2 in equation (8) was minimized. The control parameters were determined by solving equation (9) iteratively until the performance index J_2 is less than 10^{-3}. The performance criteria ξ and ω_n were chosen as 0.8 and 0.4 for process 1, 0.8 and 0.1 for process 2. The determined control parameters are shown in Table 2.

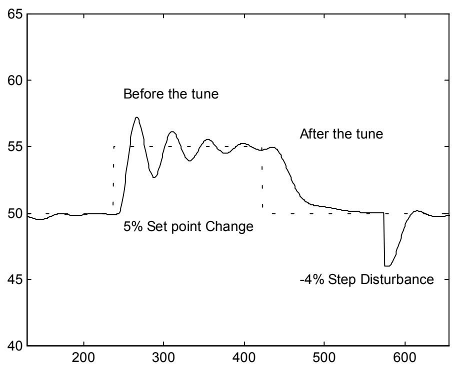
Table 2 Determined control parameters.

Control parameters		PI parameters		PID parameters		
		K_p	T_i	K_p	T_i	T_d
Process 1	2-nd order	1.099	8.594	1.067	7.110	0.975
	3-rd order	1.098	8.571	1.067	7.093	0.976
Process 2	2-nd order	0.868	18.517	0.860	14.797	5.359
	3-rd order	0.867	18.436	0.860	14.727	5.429

Fig. 4 shows the control responses of processes 1 and 2 after tuning the controller using the 2-nd order PI parameters. It shows the setpoint following and disturbance rejection performance of the controller. After tuning, the controller shows reduced overshoot and rise time, and it also shows improved disturbance rejection performance. The advantage of the developed auto-tuning system is that it can be applied to the processes while they are in normal operation.



(a) Process 1



(b) Process 2

Fig. 4 Control responses of the processes.

5. CONCLUSIONS

The auto-tuning system can access power plant field easily because it was developed using portable computer and data acquisition part. The system measures the controller and process output signals for appropriate time interval, estimates the unknown process model, and determines the optimal control parameters such that it minimizes the predefined performance index. The performance index used in this system is the average mean squared error between the closed-loop step response of the control process and the desired closed-loop step response. The system also provides the analysis function to compare the stability and performances of old and new control parameters. The system was tested for the various process models to verify its performance. Because it is possible to estimate the process without using any special test signal generator, this method can be applied to the processes such as nuclear power plant control system. In the future study, it is required to implement the system for the real control processes of the nuclear power plants in order to add up practical aspects of considerations.

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