Temperature Control Using Improved Autotuning PID Control Methods

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Abstract - This paper firs reviews different types of autotuning PID controller methods. These methods are then applied to the experiment set (an oven) designed before and the results are discussed to be able to define the best method for the set.

In this study, for achieving these controls, a digital signal processing unit is designed and a power unit including an IGBT and an IGBT driver is produced. Since the control method is wanted to be flexible, it is achieved by using a computer. So, the control is achieved by applying necessary amount of energy to the heater.

I. INTRODUCTION

PID controllers are standart tools for industrial applications. Because, they are simple and robust. But it is difficult to define the PID controller parameters properly. Therefore autotuning methods are developed. These methods enable the control practical and accurately.

II. AUTOTUNING METHODS

Here, some autotuning methods are given.

A. The Ziegler-Nichols Step Response Method

The method uses only two of the parameters shown in Fig. 1, namely a and τ . The regulator parameters are given in Table 1. The Ziegler-Nichols tuning rule was developed by empirical simulations of many different systems. The rule has the drawback that it gives closed-loop systems that are often too poorly damped.

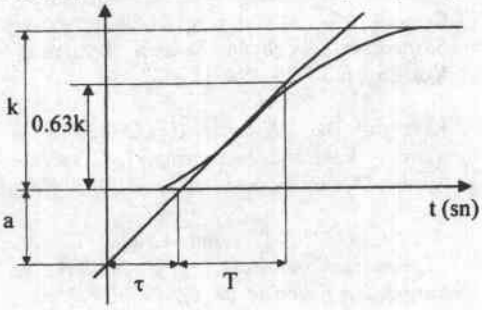

Fig.1. Unit step response of a typical industrial process.

Systems with better damping can be obtained by modifying the numerical values in Table 1. If the time constant T is also determined , an empirical rule is established that the Ziegler-Nichols rule is applicable if $0.1 < \tau/T < 0.6$. For large values of τ/T it is advantageous to use other tuning rules or control laws that compensate for dead time. For small values of τ/T, improved performance may be obtained with higher-order compensators [1].

Table 1. Regulator parameters obtained by the Ziegler – Nichols step response method.

Controller	K_P	K_I	K_D
P	1/a	-	-
PI	0.9/a	$1/3\tau$	-
PID	1.2/a	$1/2\tau$	$2/\tau$

B. Relay Method

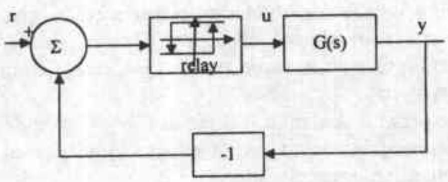

Fig. 2. Linear system with relay control.

The basic idea is the observations that many processes have limit cycle oscillations under relay feedback. A block diagram of such a system is shown in Fig. 2. The input and output signals obtained when the command signal r is zero are shown in Fig 3.

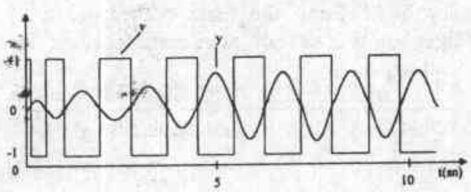

Fig. 3. Block diagram of the relay auto-tuner.

The figure shows that a limit cycle oscillation is established quite rapidly. The output is approximately sinusoidal, which means that the process attenuates the higher harmonics effectively. Let the amplitude of the square wave be d; then the fundamental componenet has the amplitude $4d/\pi$. The process output is a sinusoid with frequency ω_u and amplitude

$$a = \frac{4d}{\pi}\left|G(i\omega_u)\right| \quad (1)$$

Table 2. Regulator parameters for the Relay Method.

Controller	K_P	K_I	K_D
P	0.5 K_C	-	-
PI	0.4 K_C	1.25/ T_C	-
PID	0.6 K_C	2 / T_C	0.12T_C

To have an oscillation, the output must also go through zero when the relay switches. We can conclude that the frequency ω_u must be such that the process has a phase lag of 180°. The conditions for oscillation are thus

$$\arg G(i\omega_u) = -\pi \quad \text{and} \quad \left|G(i\omega_u)\right| = \frac{a\pi}{4d} = \frac{1}{K_c} \quad (2)$$

where K_c can be regarded as the equivalent gain of the relay for transmission of sinusoidal signals with amplitude a. This parameter is called ultimate gain. It is the gain that brings a system with transfer function G(s) to the stability boundary under pure proportional control. The period $T_c=2\pi/\omega_u$ is similarly called the ultimate period.

The controller settings are given in Table 2. These parameters give a closed loop system with quite low damping. Sytems with better damping can be obtained by slight modifications of numbers in the table. In Fig. 4, when tuning is demanded, the switch is set to T, which means that relay feedback is activated and the PID regulator is disconnected. When a stable limit cycle is established, the PID parameters are computed, and the PID controller is then connected to the process. Naturally, the method will not work for all systems. First there will not be unique limit cycle oscillations for an arbitrary transfer function. Second, PID control is not appropriate for all processes. Relay auto-tuning has empirically been found to work well for a large class of systems encountered in process control [1].

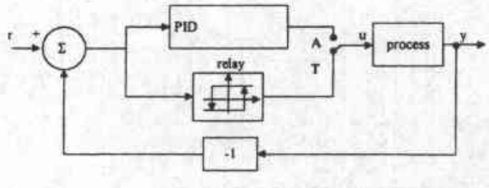

Fig. 4. Input an output of a system with relay feedback.

C. Tuning PID Controllers Using The Critical Gain And Critical Frequency

In recent years there has been much interest in the relay autotuning technique for determining the parameters of a PID controller. In this method, the PID controller is replaced by a relay so that the loop has a limit cycle. Tuning parameters of for the controller are then calculated from measured values of the amplitude and frequency of the limit cycle. Here, we therefore define the formulae for the FOPDT (First Order Plus Dead Time) plant models which enable the optimum ISTE tuning parameters to be found from these measurements of the oscillation frequency and amplitude.

To develop these tuning formulae, a relationship needs to be found between the required PID parameters and the critical point data of the plant. The critical point of the Nyquist locus is the point where the phase is 180°. the frequency is called the critical frequency, and the modulus of the gain is $1/K_c$ where K_c is the critical gain. Thus for an FOPDT process it is easily shown that

$$K_C = \frac{\sqrt{(1+\omega_c^2 T^2)}}{K}$$

$$\omega_c \tau + \tan^{-1} \omega_c T = 180 \quad (3)$$

from which the values of K_c and ω_c can be calculated. If the normalized gain $\kappa = KK_c$ is introduced, the relationships shown in Fig. 5 for κ and $\omega_c T$ plotted against the normalised dead time τ/Tcan be obtained from equations 3. Since for given FOPDT plant parameters, the plant has a unique critical point and optimum tuning parameters to satisfy the ISTE criteria, it is possible to obtain relation ships for the tuning parameters in terms of the critical point parameters of the plant. These relationships are shown in Fig. 6. The range over which the results are plotted is for τ/T from 0.1 to 2.0. The heuristic formulae given later are obtained based on a FOPDT model within a certain normalised dead time range, therefore they are usually effective over a range of the normalised gain from 1.5 to 16.

Using a least squares fit, the following empirical formulae are obtained from the results shown in Fig. 6, namely.

$K_P=0.509\, K_c$
$K_D=0.125 T_c$

$$K_I = \frac{1}{\alpha K_D} \quad (4)$$

The results for the tuning formulae derived in this way are summarised in Tables 3 and 4.Table 3 gives the formulae for PI for both set point and disturbance inputs and Table 4 the corresponding formulae for PID tuning and, in addition, PID tuning formulae for set point change with the derivative, including filter, in the feedback. The below formulae have been developed based on known critical point data, namely the critical frequency and critical gain. When performing relay autotuning, the approximate critical point data is found from the limit cycle data, namely the oscillation frequency ω_o and the peak amplitude a_o, which is used to calculate K_o, the approximate critical gain. K_o is found using the describing function for the relay, that is $K_o = 4d/a_o\pi$. For the FOPDT plant, the exact value of ω_o and K_o can be calculated using the Tsypkin method so that their relationship to ω_c and K_c can be found. It

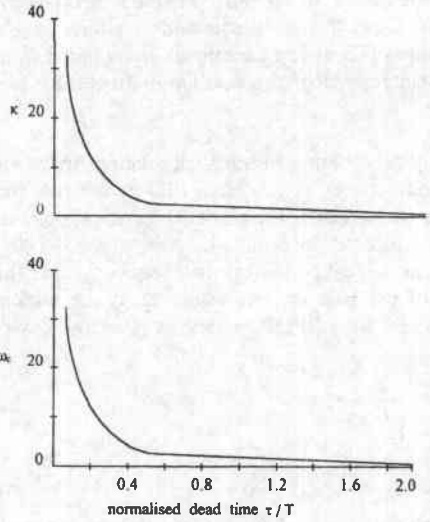

Fig. 5. Relations between κ and τ/T, ω_c and τ/T.

Table 3. PI tuning formulae for ISTE criterion

	set point	disturbance
K_P	0.361 Kc	$\frac{1.892\kappa + 0.244}{3.249\kappa + 2.097}$ Kc
K_I	$\frac{1}{0.083(1.935\kappa + 1)T_C}$	$\frac{0.7229\kappa + 1.2736}{(0.706\kappa - 0.227)T_c}$

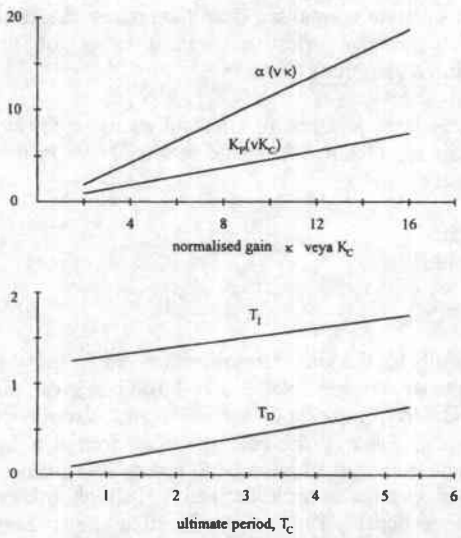

Fig. 6. Relations between PID parametersand critical point data.

Table 4. PID tuning formulae for ISTE criterion

	set point	disturbance	with D in feedback
K_P	$0.509K_C$	$\frac{4.434\kappa - 0.966}{5.12\kappa + 1.734} K_C$	$\frac{4.437\kappa - 1.587}{8.024\kappa + 1.435} K_C$
K_I	$\frac{1}{0.051(3.302\kappa + 4)T_C}$	$\frac{(3.776\kappa + 1.388)}{(1.751\kappa - 0.612)T_C}$	$\frac{1}{0.037(5.89\kappa + 1)T_C}$
K_D	$0.125\ T_C$	$0.144\ T_C$	$0.112\ T_C$

Table 5. PI tuning formulae for ISTE criterion

	set point	disturbance
K_P	$\frac{1.506\kappa_o - 0.177}{3.341\kappa_o + 0.606} K_o$	$\frac{4.126\kappa_o - 2.610}{5.848\kappa_o - 1.06} K_o$
K_I	$\frac{1}{0.055(3.616\kappa_o + 1)T_o}$	$\frac{(5.539\kappa_o + 5.036)}{(5.352\kappa_o - 2.926)T_o}$

Table 6. PID tuning formulae for ISTE criterion

	set point	disturbance	with D in feedback
K_P	$0.604\ K_C$	$\frac{6.068\kappa_o - 4.273}{5.758\kappa_o - 1.058} K_o$	$\frac{2.354\kappa_o - 0.696}{3.363\kappa_o + 0.517} K_o$
K_I	$\frac{1}{0.04(4.972\kappa_o + 1)T_o}$	$\frac{(2.516\kappa_o - 0.505)}{(1.1622\kappa_o - 0.748)To}$	$\frac{1}{0.271\kappa_o T_o}$
K_D	$0.130\ T_o$	$0.15\ T_o$	$0.116\ T_o$

is therefore possible to obtain the above formulae in terms of the values of ω_o and K_o which will be found from the limit cycle measurement when using relay autotuning. These tuning formulae are given in Tables 5 and 6 [2].

III. THE EXPERIMENTAL RESULTS

A. The Experiment Set

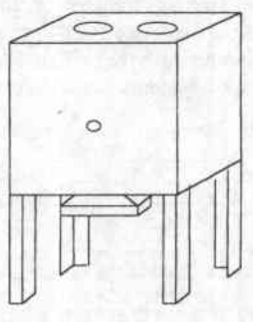

Fig. 7. The designed experiment set

The experiment set is shown in Fig. 7. It has two volumes, internal and external. The distance between two volumes there is a 2.5 cm space. To isolate the internal side of the set from outside, 2 cm thick isolation material is fixed in this space. External volume is (25x25x30) cm and internal volume is (20x20x25) cm. There are two holes on the top of the set to be used for disturbances. A 800 W resistance is put on the internal bottom of the experiment set for heating the internal volume. A termocouple temperature sensor is fixed into the middle point of the front side of the set.

B. The Block Diagram of The Whole Control System

The schematic of the whole control system is shown in Fig. 8. In this fig. a digital signal processing unit is designed and a power unit including an IGBT and an IGBT driver is produced. This power unit uses PWM (Pulse Width Modulation) technique. Since the control method is wanted to be flexible, it is achieved by using a computer. The digital signal processing unit gets the temperature data from the experiment set by using a termocouple temperature sensor and makes the data appropriate for the computer. Then, this unit transmits the data to the computer by using an RS-232 protocol. The computer produces control data by using the control method. Afterwards, this control data is transmitted to the digital signal processing unit again. This unit derives a PWM signal from the control data. And, this PWM signal is applied to the power unit. Finally, the PWM signal determines the energy level of the heater. So, the control is achieved by applying necessary amount of energy to the heater. In the digital signal processing unit PIC17C44 microcontroller and ADS1212 ADC are used. The power unit includes M57959AL Mitsubishi IGBT driver and IXSH45N120 IGBT power transistor.

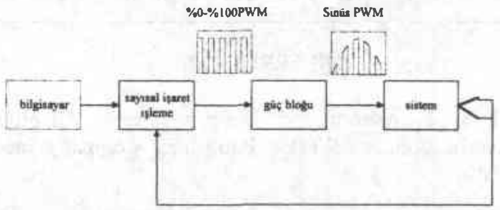

Fig 8. The block diagram of the whole control system

C. The PID Parameters Calculated for Different Autotuning Methods and The System Response To These Methods

In this section, the PID parameters calculated for different autotuning methods and the system response to these methods are given.

Table 7. The K_P value calculated for Relay Method P controller.

Cont.	Relay method P cont.
K_P	27.322

Table 8. The K_P, K_I values calculated for different autotuning PI control methods.

Cont.	Relay PI	ISTE Set Point PI	ISTE Dist PI
K_P	21.858	18.517	17.876
K_I	0.0021	0.0065	0.007

Table 9. The K_P, K_I and K_D values calculated for different autotuning PID control methods.

Cont.	Relay PID	ISTE Set Point PID	ISTE Dist PID tun.
K_P	32.786	33.004	21.865
K_I	0.0033	0.0068	0.0078
K_D	71.976	77.974	95.968

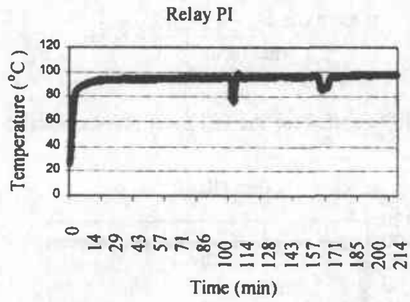

Fig 9. PI control for the relay method.

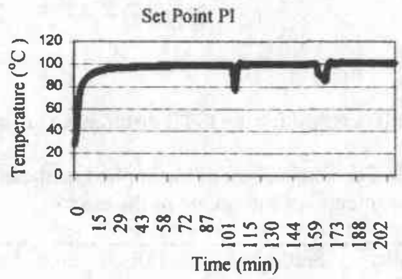

Fig 10. PI control for the ISTE set point criterion.

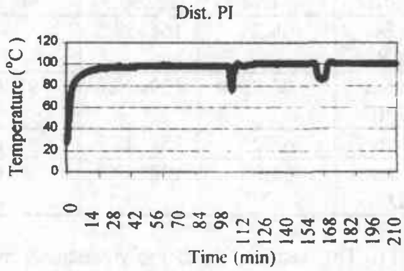

Fig 11. PI control for the ISTE disturbance criterion

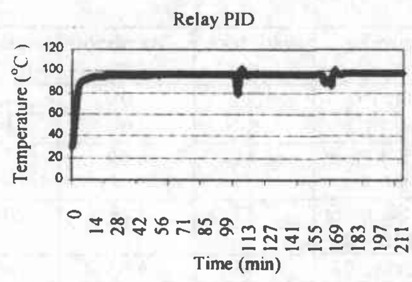

Fig 12. PID control for the Relay Method.

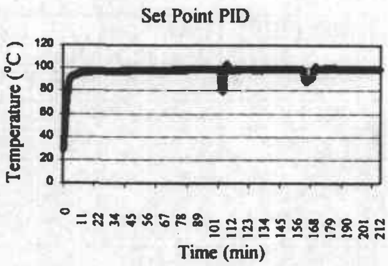

Fig 13. PID control for the ISTE set point criterion

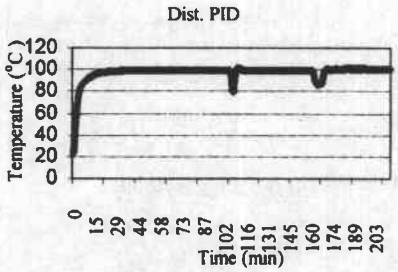

Fig 14. PID control for the ISTE disturbance criterion.

Table 10. The comparison of the applied methods.
ISE : (the integral of the square of the error)

Controller	Settl. time (min)	ISE	Settl. Temp. (°C)
Relay PI.	105.8	171729	95.43
Relay PID	71.91	18266.3	96.71
ISTE Set Point PI	68.25	166418.2	99
ISTE Set point PID	86.25	139405.8	98.78
ISTE dist. PI	68.25	151147.2	98.47
ISTE dist. PID	35.08	128259.5	99.6

Table 11. The settling time, the overshoot and the undershoot of the system response to the applied methods when the firt disturbance is given to the system.

Controller	Settl. time (min)	Overshoot (°C)	Undershoot (°C)
Relay PI.	3.33	0	24.99
Relay PID.	8	0	21.88
ISTE Set Point PI	6.41	0.59	23.16
ISTE Set point PID	7.83	3.69	20.88
ISTE dist. PI	6.66	0.35	24.76
ISTE dist. PID	4.66	1.29	20.8

The system responses are shown in Fig. 9-14. The first disturbance is applied to the system 105 minutes and the second one is 161 minutes later.

The system responses for different methods are given in Table 10. From this table it can easily be understood that the best method for the experiment set used in this study is the PID control for the ISTE disturbance criterion. Because it has got a system response with the smallest settling time, nearest settling temperature and the smallest ISE. The settling time, the overshoot and the undershoot of the system response to the applied methods are shown in Table 11 and 12 when the first and the second disturbances are given to the experiment set.

Table 12. The settling *time*, the overshoot and the undershoot of the system response to the applied methods when the second disturbance is given to the system.

Controller	Settling time (min)	Overshoot (°C)	Undershoot (°C)
Relay PI.	5	0	14.83
Relay PID.	10	0	11.69
ISTE Set Point PI	12.55	1.86	14.92
ISTE Set point PID	7.66	1.28	12.15
ISTE dist. PI	12.48	1.74	14.56
ISTE dist. PID	7.46	0.81	13.83

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