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PID AUTO-TUNING ALGORITHM FOR PROCESSES WITHOUT TIME DELAY

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Abstract: This paper presents a rather unusual application of the widely used relay feedback-based auto-tuning technique for stable SISO processes. The proposed method consists of two steps: process identification and controller design. First, a one-step procedure is suggested for identification of one point on the process Nyquist curve. A second-order-system (SOS) model can be obtained and used for controller design based on the internal model method-IMC applied to PID control. No prior information on the process parameters is required. Booth simulation and experimental results for process identification and auto tuning algorithm are presented.

Key Words: auto-tuning, PID controllers, IMC-PID design, relay experiment, temperature control.

1. INTRODUCTION

Despite the development of more advanced control strategies, the majority of controllers used in industrial instrumentation still are of the PID type. Their popularity is easy to understand - they have a simple structure, their principle is well understood by engineers and their control capabilities have proven to be adequate for most control loops. Moreover, due to process uncertainties, a more sophisticated control scheme is not necessarily more efficient than a well-tuned PID controller. However, it is common that the user often poorly tunes PID controllers because the choice of controller parameters requires professional knowledge. To simplify this task and to reduce the time required for it, many PID controllers nowadays incorporate *auto-tuning* capabilities, i.e. they are equipped with a mechanism capable of computing the 'correct' parameters automatically when the regulator is connected to the field [1].

For industrial process control a wide variety of PID controllers is currently available on the market, with features like auto-tuning. These features provide easy-to-use controller tuning and have proven to be well accepted among process engineers.

For the automatic tuning of the PID controllers, several different methods have been proposed. Some of these methods are based on identification of one point of the process frequency response, while the others are based on the knowledge of some characteristic parameters of the open-loop process step responses. The identification of a point of the process frequency response can be performed either using a proportional regulator, which brings the closed-loop system to the stability boundary or, by a relay forcing the process output to oscillate. Aström [2] reports an important and interesting approach. The method is based on the Ziegler and Nichols frequency domain design formula. A relay connected in a feedback loop with the process is used in order to determine the critical point.

The performance of the controllers tuned according to ZN rules depend strongly on the value of the process normalized dead-time (the normalized dead-time is defined for stable processes as the ratio of the apparent dead-time to the apparent time constant [3]). ZN rules often give poor damping and excessive overshoot in response to setpoint changes for processes with small values for normalized dead-time. For this type of processes we developed a method based on the identification of one point on the process Nyquist curve. The relay feedback experiment provides information to determine a second-order-system (SOS) model.

2. PROCESS

In many practical cases the process model is a first, second or a third order with no delay (tank level control, temperature control in: stirred tank heating processes, thermal treatment furnaces) [4].

Strictly applying theory, not all of these processes can be forced to oscillate by a relay. A pure relay (relay without hysteresis) can be used only if process Nyquist curve crosses the negative real axis, while an integrating relay (relay without hysteresis which has as input the integral of the error) is suitable if it crosses the negative imaginary axis. In fact, considering that in any digital controller implementation the sampling process itself introduces a phase lag and that in real situations the process output is filtered it can be assumed that all the processes in practical cases will oscillate when a relay controller is connected. Unfortunately, the pure relay experiment gives small values for the amplitude and the period of oscillation in absence of hysteresis. In these conditions the tuning obtained by the ZN methods can often be improved significantly by using other methods [5].

In this paper, the process is considered SISO (Single Input, Single Output) and described as a linear system with transfer function $H_p(s)$. The transfer function is assumed to have essentially only real, stable poles:

$$H_p(s) = \frac{k_p}{\prod_{j=1}^{n}(T_j s + 1)} \tag{1}$$

where $T_j > 0$ $(j=1, ..., n)$. Satisfactory control performances are obtained even if the transfer function has some complex, stable poles.

We assume that $H_p(s)$ is not known and that only a second-order-system (SOS) model approximation of it will be available performing proposed identification method.

3. AUTOMATIC TUNING METHOD

A standard PID control system with single input, single output, as shown in figure 1 is considered.

The PID controller has a non-interacting structure cascaded with a first order filter.

$$H_c(s) = K_c\left(1 + \frac{1}{sT_i} + sT_d\right)\frac{1}{T_f s + 1} \tag{1}$$

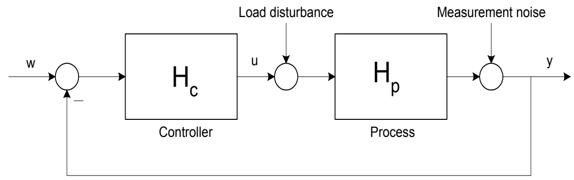


Figure 1. Control system structure

For the purpose of identification and control, higher order models are of limited utility even if the process dynamics are theoretically of high order. From the control point of view complex process models lead to complex controllers. Several papers on PID control are based on the idea of using second order with time delay models. In this paper it is assumed that the process dynamics can be described with sufficient accuracy by a second-order-system (SOS) model as:

$$H_p(s) = \frac{k_p}{\tau^2 s^2 + 2\zeta\tau s + 1}\ ,\ \tau, \zeta > 0 \tag{2}$$

In order to tune the PID controller we use IMC-PID design method [6] and we obtain:

$$K_c = \frac{2\zeta\tau}{k_p 2T_c},\quad T_i = 2\zeta\tau,\quad T_d = \frac{\tau^2}{2\zeta\tau},\quad T_f = \frac{T_c}{2} \tag{3}$$

leading to a closed loop transfer function:

$$H_0(s) = \frac{H_p(s)\cdot H_c(s)}{1 + H_p(s)\cdot H_c(s)} = \frac{1}{(T_c s + 1)^2} \tag{4}$$

The parameters of the process transfer function are assumed to be unknown and have to be estimated using the relay feedback experiment.

Performing the relay feedback experiment the value of the process transfer function at frequency ω_1 is obtained, i.e.:

$$H_p(j\omega_1) = a_1 + jb_1 \tag{5}$$

The parameters a_1 and b_1 can be obtained using a relay feedback experiment. In order to identify a point on the process Nyquist curve, a relay connected in a feedback loop with the process is used, forcing the process output to oscillate. Using an integrating relay, the calculations are less complex than using a relay with hysteresis. The point given by the intersection of the process Nyquist curve and the negative imaginary axis is identified:

$$a_1 = 0,\qquad b_1 = -\frac{\pi h}{4d},\quad \omega_1 = \frac{2\pi}{T_1} \tag{6}$$

where d is the relay amplitude, respectively h and T are the process output oscillation amplitude and period.

The real and imaginary components of $H_p(j\omega_1)$ can be written as:

$$\begin{aligned} a_1 &= \mathrm{Re}\left(H_p(j\omega_1)\right) = \frac{k_p\left(1-\tau^2\omega_1^{\ 2}\right)}{\left(1-\tau^2\omega_1^{\ 2}\right)^2 + \left(2\zeta\tau\omega_1\right)^2} = \frac{\left(1-\tau^2\omega_1^{\ 2}\right)M_1^{\ 2}}{k_p} = 0 \\ b_1 &= \mathrm{Im}\left(H_p(j\omega_1)\right) = \frac{k_p(-2\zeta\tau\omega_1)}{\left(1-\tau^2\omega_1^{\ 2}\right)^2 + \left(2\zeta\tau\omega_1\right)^2} = \frac{-2\zeta\tau\omega_1 M_1^{\ 2}}{k_p} \end{aligned} \tag{7}$$

where

$$M_1^{\ 2} = \frac{k_p^{\ 2}}{\left(1-\tau^2\omega_1^{\ 2}\right)^2 + \left(2\zeta\tau\omega_1\right)^2} = a_1^{\ 2} + b_1^{\ 2} = b_1^{\ 2}$$

Therefore, we obtain:

$$\tau^2 = \frac{1}{\omega_1^{\ 2}} \qquad 2\zeta\tau = -\frac{k_p}{\omega_1 b_1} \tag{8}$$

To perform relay feedback experiments, the process is first brought to steady-state conditions in manual control or with any stable PI controller. Measuring steady-state values u_0 and y_0, the controller and process output, giving then a small perturbation to the control manipulated variable and measuring its effect on the process output, the process gain k_p can be easily determined.

Now, the PID controller parameter can be rewritten:

$$K_c = -\frac{1}{2T_c\omega_1 b_1}, \quad T_i = -\frac{k_p}{\omega_1 b_1}, \quad T_d = -\frac{b_1}{\omega_1 k_p}, \quad T_f = \frac{T_c}{2} \tag{9}$$

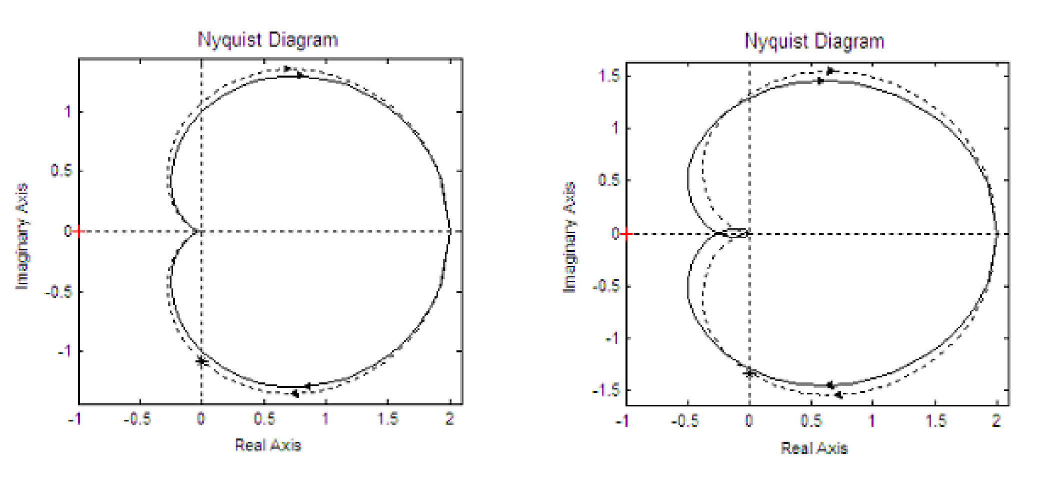
where T_c is a design parameter, specifying the closed loop bandwidth.

4. SIMULATION

First we tested the proposed identification method on 2 examples. The process transfer functions are given by

$$H_{p1}(s) = \frac{2}{(120s+1)^2}, \quad H_{p2}(s) = \frac{2}{(80s+1)^3} \tag{10}$$

We identified a second-order-system (SOS) model (equation 2). The results of the identification with the proposed method are shown in Figure 2.



a) **b)**

Figure 2. Nyquist plot of the process given by the transfer function (10) (solid line) and of the process model identified using the relay experiment (dotted line)., a) H_{p1} case, b) H_{p2} case

The proposed auto-tuning algorithms have been tested by simulated examples. In figure 3 are presented the results for processes of the 1 to 4th order (11).

$$H_p(s) = \frac{2}{\left(\frac{240}{i}s+1\right)^i}, \quad i=1,\ldots 4. \tag{11}$$

Different aspects, such as process dynamics, setpoint changes and load disturbances are analyzed.

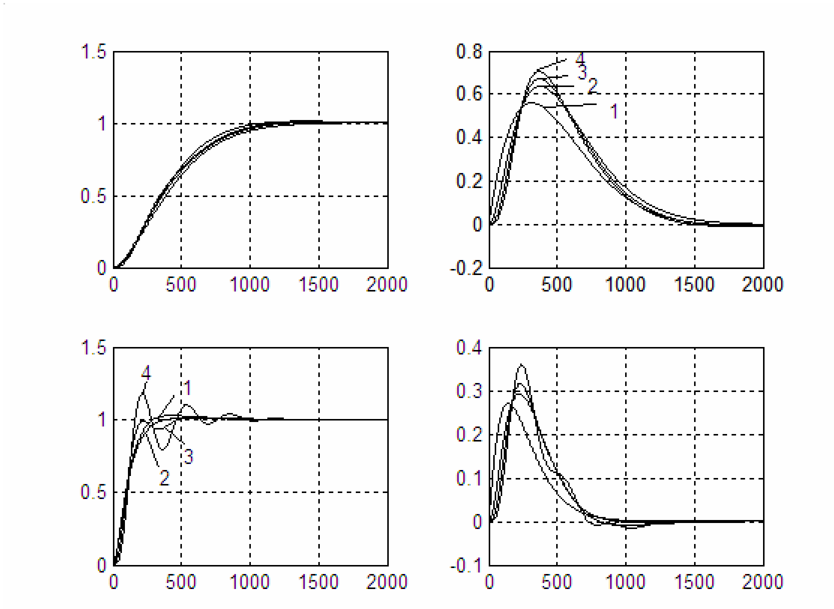


Figure 3. The closed loop step responses and the load disturbance responses for the processes given in (11)

The simulations were carried out in MATLAB environment. The amplitude of the setpoint and the load disturbance is 1. The closed loop step responses are presented in the left plots and the load disturbance responses in the right plots. The design parameter - T_c can be specified by the user or can be chosen automatically as a percent of $2\zeta\tau$. Here T_c is fixed at $(2\zeta\tau)/2$ for the upper plots and respectively $(2\zeta\tau)/10$ for lower plots.

5. EXPERIMENTAL RESULTS

For experimental results the auto-tuning algorithm was implemented on a PC computer equipped with a data acquisition board and small laboratory processes were controlled. Figure 4 shows the results when the auto-tuner was applied to temperature control of a thermal plant.

The process was first brought to steady-state conditions in manual control (θ_0=80ºC, u_0=0.28). A sampling period of 1 second was used in all of the experiments. The results of the integrating relay experiment are shown in figure 4.a) and the closed loop step response in figure 4.b). The design parameter T_c is fixed at $(2\zeta\tau)/2$ for the plots (1), at $(2\zeta\tau)/4$ for the plots (2) and respectively $(2\zeta\tau)/8$ for the plots (3). The experimental results are plotted with solid line and the simulation results, obtained using the model identified from integrating relay experiment, with dotted line.

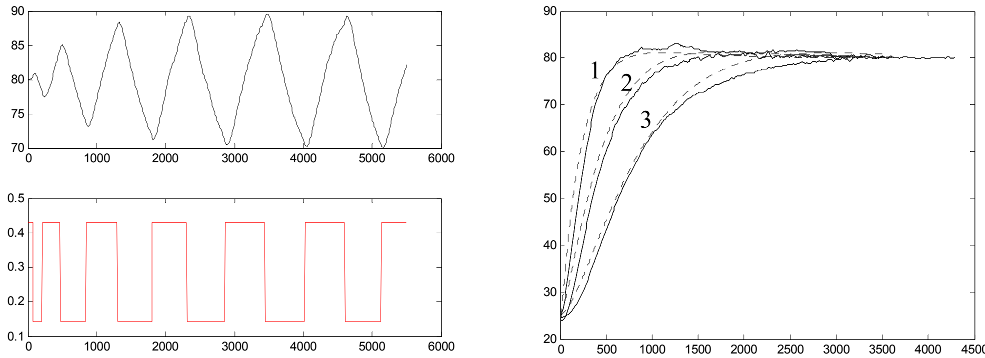


Figure 4. The experimental results of the auto-tuner applied to temperature control: a) integrating relay experiment, b) closed loop step response

6. CONCLUSIONS

A relay based algorithm for auto-tuning of PID controllers has been presented, assuming a process model structure and achieving the regulator tuning by identifying one point of the process frequency response and using IMC-PID design method.

This auto-tuning method yields PID parameters only for a restricted class of process models (delay-free stable processes). It is not a general methodology for arbitrary process models.

Concerning the complexity of the method, the proposed methods involve simple calculations and the experiments are easy to be performed.

Experiments and simulation studies have indicated that the presented self-tuner performs well and can be easily used even by people who are not specialists in automatic control.

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