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Research note

On-line identification of cascade control systems based on half limit cycle data

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ABSTRACT

An on-line identification procedure is presented for cascade control systems in which both inner and outer loop process dynamics are modelled simultaneously by performing a single experiment. Departing from the conventional relay autotuning method where the controller is replaced by a relay, the proposed method is carried out on-line without breaking the closed-loop control. Exact analytical expressions are derived for process model parameters in terms of a few critical parameters of half period data of limit cycle output. Simulation examples are included to demonstrate the effectiveness of the proposed method.

1. Introduction

Cascade control helps in eliminating the effect of load disturbance and improving the dynamic performance of a closed-loop system over a single-loop control [1]. Generally a cascade control structure is to nest one feedback loop inside another feedback loop involving the use of primary (or master) and secondary (or slave) controllers.

The standard conventional approach of tuning these cascade controllers is often ineffective because it ignores strong interaction between the two loops. Also the widely used two-step approach is a fairly time consuming task due to the approach being sequential in nature and problems related to master and slave signal tracking. Thus it would be very useful to realize the automatic tuning procedure for cascade control system (CCS) in which the entire tuning process is carried out in one experiment.

Relay-based autotuning proposed by Åström and Hägglund [2] was one of the first to be commercialized and has remained attractive owing to its simplicity and robustness (see [3,4] and references within). Ou and Wu [5] provided an adaptive least-squares algorithm for cascade control which is not suitable for processes with large dead time and also the on-line experiment time by their method is very long. Autotuning methods for cascade control strategies have been published by Hang et al. [6], Song et al. [7] and Kaya et al. [8], however their procedures are based on the off-line relay test. Off-line tuning has associated implications in the tuning-control transfer, affecting operational process regulation which may not be acceptable for certain critical applications [9]. Although individual controller tuning has been automated in [6] and [8], the sequential nature of the tuning procedure remains unchanged. Tan et al. [9] has suggested an on-line relay tuning approach in one experiment, but the experiment requires a priori information of the process. Also, the ultimate frequency used by them for the outer-loop design is based on initial ultimate frequency without considering changes to the inner-loop control parameters. Lee et al. [10] have proposed IMC based tuning rules for the primary and secondary controllers, but it has not been specified how the procedure can be automated. Visioli and Piazzi [11] have proposed an automatic tuning method for the CCS but the method consists of an open-loop step test for estimation of process dynamics and command signal generator for setpoint tracking. Sadasivarao and Chidambaram [12] have presented an iterative method based on a genetic algorithm for tuning cascade controllers. The on-line experiment time by the method is very long which may not be acceptable in practice. Alfaro et al. [13] made use of a two degrees of freedom design approach for a cascade control configuration for smooth control by introducing additional parameters that need to be tuned appropriately. Tuning methods for parallel cascade control are discussed in [14,15] with the process information assumed to be known in the form of the first order plus time delay (FOPDT) model.

The objective of this paper is to develop an on-line autotuning method for the CCS with the help of a single relay feedback test. By employing a relay in parallel to the master controller, both inner and outer process dynamics are simultaneously identified from the respective half limit cycle outputs. Differently from the standard relay autotuning approach, it allows the tuning of the controller

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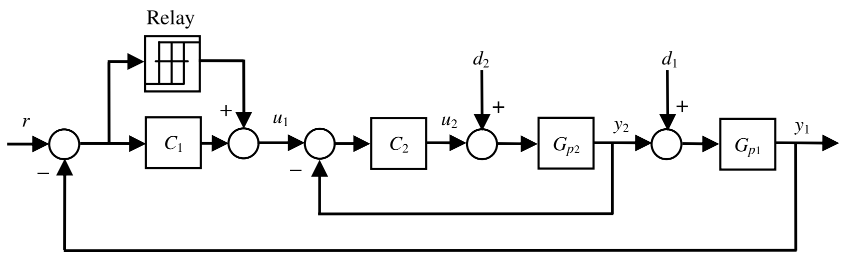

Fig. 1. Structure for on-line tuning of the cascade control system.

in the presence of a static load disturbance without resetting the relay. Simple analytical tuning rules proposed by Skogestad [16], that do not require iterative calculations, are considered for the controller settings. This method overcomes the requirements of the sequential conventional approach for tuning the CCS.

2. On-line identification

The configuration of the CCS is shown in Fig. 1 where, C_1 and C_2 are the master and slave controllers while G_{p1} and G_{p2} are the outer and inner loop processes, respectively. Fig. 1 shows the on-line tuning scheme for the CCS by employing a relay in parallel with the master controller without disturbing the closed-loop control. The relay height is increased from zero to some acceptable value when re-tuning is necessary. Based on the induced limit cycle oscillations y_1 and y_2, the process dynamics are first identified and then fine tuning of the existing controllers are accomplished.

To make the cascade control effective, the following guidelines are to be incorporated.

- The inner loop should be faster than the outer loop at least by five times and it should be possible to have a high gain in order to regulate disturbances more effectively [17].
- In the absence of default control settings, C_1 and C_2 are proportional-integral (PI) and proportional (P) type controllers, respectively. These settings are intended primarily for the purpose of stabilizing the process during the tuning procedure. Practical applications of autotuning methods have been mainly to derive more efficient updates of current or default control settings, which are already available in many cases.

Let the process dynamics be represented by the first order rational transfer function model with dead time

$$G_i(s) = k_i e^{-\theta_i s}/(\tau_i s + 1) \tag{1}$$

where, $i = 1$ for the outer and $i = 2$ for the inner process model. Although, the model structure is simple with only three model parameters, yet it is one of the most common and adequate ones used, especially in the process control industries [17].

2.1. Estimation of the inner process model

A relay autotuning test yields interesting results as shown Fig. 2 due to faster dynamics and higher gain of the inner loop compared to the outer loop. The output y_2 is constant at least over a half period and acts as a constant input for the outer process during that period. Therefore, it is possible to obtain the analytical expressions for half limit cycles y_1 and y_2 (Fig. 3) from a single relay test.

Let the relay amplitudes and hysteresis widths be $\pm h$ and $\pm\varepsilon$, respectively. Following the limit cycle analysis given in [18], the state and output expressions for $G_2(s)$ in (1) are written in the time domain controllable canonical form as

$$\begin{aligned} \dot{x}_2(t) &= \lambda x_2(t) - k_2\lambda u_2(t-\theta_2) \\ y_2(t) &= x_2(t) \end{aligned} \tag{2}$$

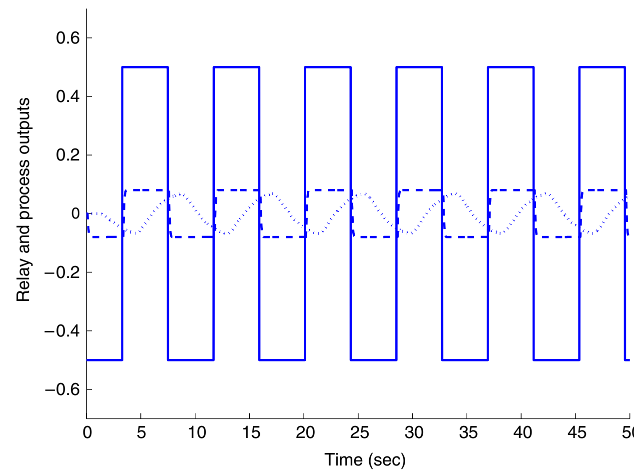

Fig. 2. Responses from the relay test, — relay output, – – $y_2(t)$ and · · · $y_1(t)$.

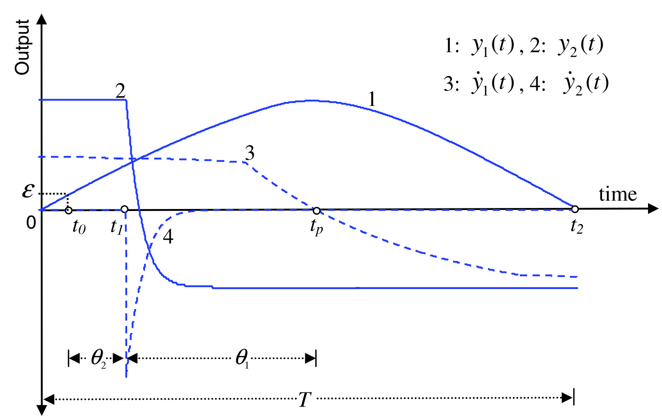

Fig. 3. Half cycle of the limit cycle outputs.

where, $\lambda = -1/\tau_2$. The relay switches from h to $-h$ at time $t = t_0$ due to hysteresis and provides two different piecewise constant input signals during a half period of the process output. The solution of (2) for $t \geq t_1$ where the input signal $u_2(t-t_1) = -h$ can simply be

$$y_2(t) = y_2(t_1)e^{\lambda(t-t_1)} - k_2 h(1 - e^{\lambda(t-t_1)}). \tag{3}$$

Now the inner loop transfer function is

$$T_2(s) = \frac{Y_2(s)}{U_1(s)} = G_2C_2(s)[1 + G_2C_2(s)]^{-1} \tag{4}$$

with $C_2(s) = k_{p2}$ during an on-line relay test. Substitution of $G_2(s)$ and $C_2(s)$ in (4) gives

$$T_2(s) = \frac{k_2 k_{p2} e^{-\theta_2 s}}{\tau_2 s + 1 + k_2 k_{p2} e^{-\theta_2 s}}. \tag{5}$$