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Improved automatic tuning of PID controller for stable processes

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ABSTRACT

This paper presents an improved automatic tuning method for stable processes using a modified relay in the presence of static load disturbances and measurement noise. The modified relay consists of a standard relay in series with a PI controller of unity proportional gain. The integral time constant of the PI controller of the modified relay is chosen so as to ensure a minimum loop phase margin of 30°. A limit cycle is then obtained using the modified relay. Hereafter, the PID controller is designed using the limit cycle output data. The derivative time constant is obtained by maintaining the above mentioned loop phase margin. Minimizing the distance of Nyquist curve of the loop transfer function from the imaginary axis of the complex plane gives the proportional gain. The integral time constant of the PID controller is set equal to the integral time constant of the PI controller of the modified relay. The effectiveness of the proposed technique is verified by simulation results.

1. Introduction

Despite the numerous existing procedures, much attention has been given in recent years to methods for the design of PI/PID controllers. The main reason is that the controllers are simple, easy to implement and give good performance. Åström and Hägglund [1] introduced a relay based method for the automatic tuning of PID controller using phase and gain margin specification. The relay auto-tuning method is based on the critical point (critical gain and critical frequency) which lies on the negative real axis of the complex plane. Thereafter, the accuracy and efficiency of the relay auto-tuning have been improved by several authors. Scali et al. [2] identified a point in the third quadrant using a modified relay (time delay along with the relay) for the identification of a completely unknown process. However, their method requires several relay tests to know the time delay of the modified relay. Also, the delay used during the identification is independent of controller parameters. It is shown that [3] the accuracy of the describing function can be improved using an integrator along with the standard relay during identification as per the attenuation characteristic of an integrator. The real process is approximated by a low order transfer function model and the PID controller is designed by the pole-zero cancellation principle for a specified phase and gain margin. The approximations used by their method fail to give good results for many typical process models. A relay feedback tuning method with iso-damping property is proposed by Chen et al. [4] to design a robust PID controller. However, the method gives oscillatory closed loop response. Ho et al. [5] incorporated the ideas from iterative feedback tuning (IFT) into relay auto-tuning of PID controller to give specified phase margin and bandwidth. Some limitations of the standard relay auto-tuning technique using a version of the Ziegler–Nichols formula [6] were overcome by their method. A modified relay feedback approach for controller tuning based on the assessment of gain and phase margins is proposed by Jeng et al. [7]. But, the experiment time of the methods is more which may not be acceptable in practice.

In this paper, we propose a modified relay based automatic tuning method for stable processes. The proposed method has the following advantages. Firstly, the method estimates the critical gain and critical frequency more accurately than the existing conventional relay auto-tuning methods due to the presence of the PI controller in the modified relay. Secondly, the auto-tuning method gives a symmetrical and smooth limit cycle output in the presence of static load disturbance and measurement noise thereby improving the measurement accuracy of the critical gain and critical frequency. Finally, the method does not require prior information about the process and needs to design only two controller parameters (a proportional gain and a derivative time constant) from the modified relay experiment.

This paper is organized as follows. Section 2 describes the proposed modified relay auto-tuning method. In Section 3, the proposed method is illustrated through different simulation examples. Finally, the conclusion is given in Section 4.

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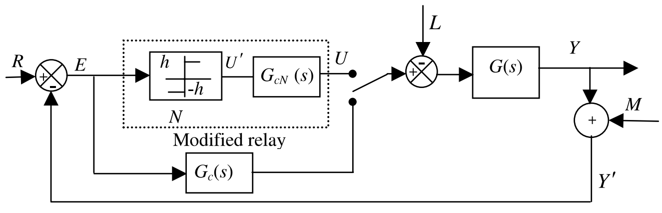

Fig. 1. Proposed auto-tuning scheme.

2. Modified relay auto-tuning method

2.1. Auto-tuning scheme

The proposed auto-tuning scheme is shown in Fig. 1. The modified relay comprises an ideal relay, N, connected in series with a PI controller of unity proportional gain, $G_{cN}(s)$. The static load disturbance L and the random additive noise M appear at the input and output of the process, respectively. The auto-tuning of PID controller is carried out based on the criterion that the closed loop system maintains a phase margin of at least 30° during the process identification and control. The forms of G_{cN} and G_c considered in the proposed scheme are

$$G_{cN}(s) = \left(1 + \frac{1}{T_I s}\right) \quad (1)$$

$$G_c(s) = K_c\left(1 + \frac{1}{T_I s}\right)\left(1 + \frac{T_d s}{1 + \beta T_d s}\right) = G_{cN} G_{cPD} \quad (2)$$

where T_I is the integral time constant, T_d is the derivative time constant, K_c is the proportional constant, β is the derivative filter constant and

$$G_{cPD}(s) = K_c\left(1 + \frac{T_d s}{1 + \beta T_d s}\right). \quad (3)$$

In this study, β is neglected for the purpose of analysis. The auto-tuning test is carried out in two stages of relay test as T_I of $G_{cN}(s)$ is unknown initially. In the initial stage, the value of T_I is chosen between 10–20 so as to induce the limit cycle output with a critical frequency ω'_{cr}. Thereafter, T_I is updated using the expression (referring (1))

$$T_I = \frac{1}{\omega'_{cr} \tan \phi'} \quad (4)$$

where, $\phi' \geq 30°$ is the user-defined phase angle.

Let the dynamic model of a stable plant be represented by $G(s) = \frac{Ke^{-\theta s}}{Ts+1}$. The open loop transfer function becomes $G_{CN}G(s) = \left(1 + \frac{1}{sT_I}\right)\frac{Ke^{-\theta s}}{Ts+1}$. Under limit cycle condition, $NG_{CN}G(j\omega'_{cr}) = -1 = \frac{Ke^{-j\omega'_{cr}\theta}}{j\omega'_{cr}T+1}$ assuming that $\omega'_{cr}T_I \gg 1$. But, when $T_I \ll 10$, the limit cycle condition becomes $NG_{CN}G(j\omega_{cr}) = -1 = \frac{j\omega_{cr}T_I+1}{j\omega_{cr}T_I}\frac{Ke^{-j\omega_{cr}\theta}}{j\omega_{cr}T+1}$ where ω_{cr} is the critical frequency at the second stage of the relay test and $\omega_{cr}T_I \ll 10$. From the above two limit cycle conditions, it is easy to express $\frac{Ke^{-j\omega'_{cr}\theta}}{j\omega'_{cr}T+1} = \frac{j\omega_{cr}T_I+1}{j\omega_{cr}T_I}\frac{Ke^{-j\omega_{cr}\theta}}{j\omega_{cr}T+1}$. Upon comparison of magnitude or phase of both sides of the equation one finds that $\omega_{cr} < \omega'_{cr}$.

The automatic tuning method is therefore applicable for all stable processes for which the initial choice of T_I in the range of 10–20 results in a limit cycle oscillation with the critical frequency ω'_{cr} such that $\omega'_{cr}T_I \gg 1$.

Therefore, the phase angle contributed by the modified relay $\phi = \tan^{-1}\left(\frac{1}{\omega_{cr}T_I}\right)$ is more than ϕ'. The Nyquist curves of the uncompensated process, the process with the modified relay and the process with the controller are shown in Fig. 2. The modified relay identifies a point in the third quadrant (Δ_1 in Fig. 2) with the critical frequency ω_{cr} that lags behind the negative real axis by an angle of ϕ. The loop phase margin ϕ_m is calculated with respect to the gain crossover point Δ_2 as shown in Fig. 2 which is more than 30° for a user-defined phase angle of $\phi' \geq 30°$ ensuring a stable limit cycle output. Once the identification is over, the PID controller is designed based on the limit cycle parameters obtained from the second stage of relay test. The integral time constant of the PID controller is the integral time constant of G_{cN}. The remaining controller parameters K_c and T_d are designed using the amplitude and frequency of the limit cycle output signal.

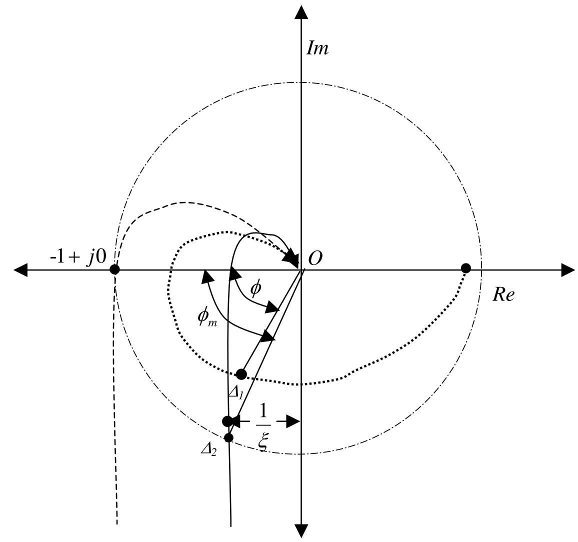

Fig. 2. Nyquist curves of the uncompensated process (···), the process with the modified relay (– – –) and the process with the controller (—).

2.2. Accuracy of proposed scheme

The describing function analysis produces accurate results only when the limit cycle is near sinusoidal and this is certainly not the case with the majority of processes. The describing function approximation leads to estimation error in the critical gain and frequency. In the proposed method, the ratios of amplitudes of the harmonic components to the fundamental decrease because of integral action of the PI controllers in the modified relay. Thus the accuracy of the describing function analysis is improved. Let $e(t) = A \sin \omega t$ be the input signal to the modified relay where A is the peak amplitude of the error signal. The ideal relay output $u'(t)$, in response to $e(t)$, is a square wave with the fundamental frequency ω. Using Fourier series expansion, the periodic output $u'(t)$ can be written as

$$u'(t) = \sum_{k=1}^{\infty} \mu'_{2k-1} \sin((2k-1)\omega t) \quad (5)$$

where $\mu'_{2k-1} = \frac{4h}{\pi(2k-1)}$ are the amplitudes of the harmonic components of $u'(t)$ and h is the relay height. The amplitude ratios of higher harmonic components to the fundamental component of ideal relay output are given in Table 1. The expression of the output of the modified relay $u(t)$ is

$$u(t) = \sum_{k=1}^{\infty} \mu'_{2k-1} \sin((2k-1)\omega t) + \sum_{k=1}^{\infty} \frac{\mu'_{2k-1}}{\omega T'_I(2k-1)} \sin\left((2k-1)\omega t - \frac{\pi}{2}\right). \quad (6)$$