Smith Predictor 의 모델오차를 고려한 PID 제어기 조율법

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A PID Tuning Method for Smith predictor in the Presence of Modeling Error

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Introduction

Time delay commonly occurs in usual chemical process control in the presence of distance velocity lags, recycle loops, and the dead time associated with composition analysis. The existence of time delay in a process transfer function causes major difficulties in the design and implementation of control algorithms. For this reason, extensive research efforts have been done on developing the efficient control method which address the problems. Smith predictor (Smith 1957) or Dead-Time Compensator (DTC) attracted many researchers and control engineers because of its simplicity and efficiency.

The effectiveness of the DTC has been limited by two major problems. One is its sensitivity to modeling error, the other is its poor disturbance rejection capability. Attempted to improve the disturbance rejection capability of the DTC have included the Modified Smith Predictor of Watanabe et al.(1987), Wong and Seborg(1986), Doss and Moore (1982) and many more. As a result, the nominal performance in disturbance rejection capability can be improved significantly. However, very few works have been addressed to improve tuning performance in the presence of modeling error.

The tuning of the PID controller with the DTC should be considered the robust stability and performance to modeling error. Morari and Zafiriou (1989) presented the tuning guideline based on one degree of freedom controller which was tuned usually for tracking set-point. Palmor and Blau(1994) also developed a tuning rule which considered the mismatches in the dead time. In this paper, we propose a simple tuning rule to incorporate the modeling error more systematically. The proposed method usefully utilizes existing PID tuning rules such as ITAE and IMC-PID. Compared with that of Palmor et al., it gives more stable closed-loop response and a better control performance for the setpoint tracking problem.

Simple Tuning Rule for Smith Predictor

Consider the feedback control system shown in Figure 1. The output of the system y(s) can be written:

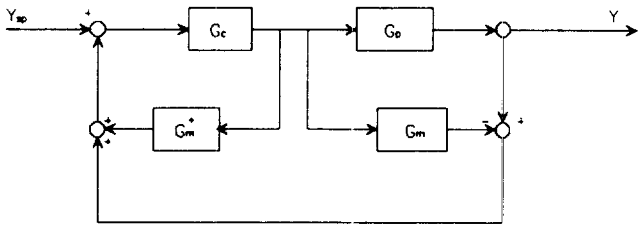

Figure 1. Block diagram of the Smith predictor

$$\frac{y(s)}{y_{sp}(s)} = \frac{G_c(s)\,(G_p(s) - G_m(s) + G_m^*(s))}{1 + G_c(s)\,(G_p(s) - G_m(s) + G_m^*(s))} \tag{1}$$

where $G_m^*(s)$ means the model excluding the time delay term from the model $G_m(s)$. Here, $G_p(s) - G_m(s) + G_m^*(s)$ can be efficiently approximated as follows:
Assume that the model is perfect except the time delay term. Then following equation is easily obtained.

$$G_p(s) - G_m(s) + G_m^*(s)$$
$$= G_m^*(s)\,(1 + \exp(-\theta_p s) - \exp(-\theta_m s)) \tag{2}$$

where θ_p and θ_m represent the time delays of the process and the model, respectively. Next, we use the first Taylor series expansion to treat the time delay term then

$$G_m^*(s)\,(1 + \exp(-\theta_p s) - \exp(-\theta_m s))$$
$$\fallingdotseq G_m^*(s)\,(1 - (\theta_p s - \theta_m s)) \tag{3}$$

and this equation can be rewritten by the following equation.

$$\fallingdotseq G_m^*(s)\,e^{-(\theta_p - \theta_m)s} \tag{4}$$

This approximation is accurate enough for the purpose of the controller tuning unless the modeling error of the time delay is too big. By substituting (4) to (1) the overall transfer function becomes

$$\frac{y(s)}{y_{sp}(s)} = \frac{G_c(s)\,G_m^*(s)\,e^{-(\theta_p - \theta_m)s}}{1 + G_c(s)\,G_m^*(s)\,e^{-(\theta_p - \theta_m)s}} \tag{5}$$

Consequently, $G_c(s)$ can be simply tuned by the usual tuning rules such as ITAE, Cohen-Coon, IMC and Ziegler-Nichols tuning rules based on the low order plus time delay model $G_m^*(s)\,e^{-(\theta_p - \theta_m)s}$.

Until now, we consider only the modeling error of the time delay. We can also consider the modeling error of the time constant term by introducing the equivalent time delay concept. The proposed equivalent time delay of $G_m^*(s)$ defined as follows.

$\theta_{equivalent} = -\frac{d}{ds}G(s)\mid_{s=0}$, here $G(0) = 1$. This is derived by matching the first and second terms of (6) and (7).

That is, $G(s) = G(0) + \frac{d}{ds}G(s)\mid_{s=0} s + \cdots\cdots$ (6)

$$e^{-\theta_{equivalent}s} = 1 - \theta_{equivalent}s + \cdots\cdots \tag{7}$$

Using the equivalent time delay concept, we can efficiently approximate the modeling error between $G_p^*(s)$ and $G_m^*(s)$. That is,

$$G_p^*(s) \doteqdot G_m^*(s)e^{-\theta_{equivalent}s} \tag{8}$$

where, $G_p^*(s)$ means the process excluding the dead time term from the process $G_p(s)$.

$$e^{-\theta_{equivalent}s} \doteqdot \frac{G_p^*(s)}{G_m^*(s)} \tag{9}$$

$$G_p(s) \doteqdot G_m^*(s)e^{-(\theta_p+\theta_{equivalent})s} \tag{10}$$

where $\theta_{equivalent} = -\frac{d}{ds}\left(\frac{G_p^*(s)}{G_m^*(s)}\right)\Big|_{s=0}$

Therefore, using (10), (1) can be transformed to the following simple equation.

$$\frac{y(s)}{y_{sp}(s)} = \frac{G_c(s)\, G_m^*(s)e^{-(\theta_p-\theta_m+\theta_{equivalent})s}}{1+G_c(s)\, G_m^*(s)e^{-(\theta_p-\theta_m+\theta_{equivalent})s}} \tag{11}$$

This equation can be represented by the following block diagram.

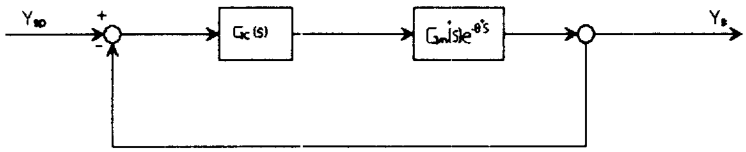

Figure 2. Simplyfied Block diagram of DTC in the presence of modeling error

where $\theta^* = (\theta_p - \theta_m + \theta_{equivalent})$ (12)

From the block diagram, we can recognize that $G_c(s)$ can be simply tuned by existing PID tuning rules such as ITAE and IMC-PID tuning rules based on the low order plus time delay model $G_m^*(s)e^{-(\theta_p-\theta_m+\theta_{equivalent})s}$.

It should be noted that the $G_p(s)$ in (1) should be chosen by the worst one to guarantee the stable closed-loop response for the all possible $G_p(s)$'s. Let us define the worst case for the FOPDT model. The worst case in the presence of the time constant and time delay modeling error is defined as the one which produces the maximum equivalent time delay.

For example, The process with following uncentainty

$$G_p(s) = \frac{e^{-(\theta_m+\triangle\theta)s}}{(\tau_m+\triangle\tau)s+1} \quad \text{here} \quad |\triangle\theta| < \delta_\theta \quad , |\triangle\tau| < \delta_\tau \tag{13}$$

The worst case is

$$G_p(s) = \frac{e^{-(\theta_m+\delta_\theta)s}}{(\tau_m+\delta_\tau)s+1} \tag{14}$$

which results in $G_p(s) \doteqdot \frac{e^{-(\theta_m+\delta_\theta+\delta_\tau)s}}{\tau_m s+1}$, $G_p(s) - G_m(s) + G_m^*(s) \doteqdot \frac{1}{\tau_m s+1} e^{-(\delta_\theta+\delta_\tau)s}$ (15)

Simulation Result

Consider the process $G_p(s) = \frac{e^{-1.5s}}{0.8s+1}$ for which we expect the maximum uncertainty as δ_θ=0.5 and δ_τ=0.2, then the process model is selected $G_m(s) = \frac{e^{-1.0s}}{s+1}$

Therefore, the overall transfer function of the control system is approximated as follows

$$\frac{y(s)}{y_{sp}(s)} = \frac{G_c(s)\frac{1}{s+1}e^{-0.7s}}{1+G_c(s)\frac{1}{s+1}e^{-0.7s}} \tag{16}$$

Figure 3. compares the closed-loop responses by Palmor et al.(1994) and the proposed method. In the proposed method, ITAE tuning rule is applied.
The resulting PI controller by the Proposed method performs better than the controller tuned by the Palmor's method.

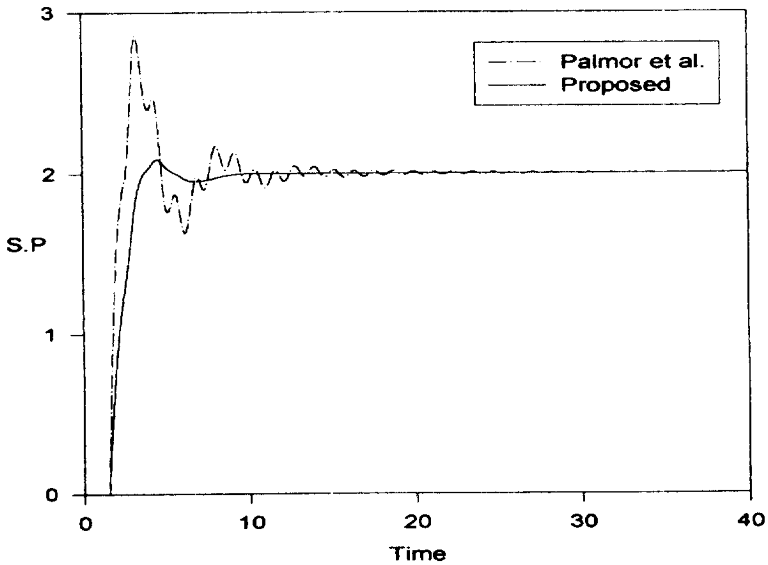

Figure 3. Simulation result

Conclusion

We proposed a new tuning method for Smith predictor in the presence of modeling error. It was shown that the proposed method gave the better control performance and robustness to the modeling error. Another important advantage of the proposed method is that it can utilize the existing tuning rules.

Acknowledgement

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