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Robustness of fuzzy PID controller due to its inherent saturation

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ABSTRACT

In this paper, an inherent saturation of the fuzzy proportional–integral–derivative (PID) controller is revealed due to the finite fuzzy rules used. An equivalent structure and model of the fuzzy rule base is derived to show a saturation property. The bandwidth of the fuzzy PID control system can be adjusted by changing saturation parameter. Parameters of the fuzzy PID controller can be designed based on the inherent saturation. Compared with the conventional PID controller, the fuzzy PID controller has two advantages because of the inherent saturation: (1) without the additional filter, it can prevent impulse signal effectively; (2) without the additional anti-windup structure, a robust performance can be maintained when the input saturation occurs. The fuzzy PID controller is applied to an integrated circuit curing process. The simulation and experiment results demonstrate these effects of the inherent saturation, and its influence to the robustness of fuzzy PID controller.

1. Introduction

In many process control systems, the impulse signal and integrator windup are two important phenomenons in application of the conventional proportional integral derivative (PID) control system. The derivative action in PID controller often generates a high-peak impulse signal when the set-point changes or disturbance appears [1,2]. This high-peak impulse signal may damage components, or even destroy the processes. In industrial processes, there exists input saturation due to physical limitations. This saturation may not be considered properly in the design process, which may cause the PID controller suffering from the windup phenomenon [1–4]. The windup often causes large and poorly decaying overshoots in the transient state, which needs to be avoided. Therefore, removing the impulsive behavior and the integrator windup are important issues in application of PID control system [1,4,5], which commonly adopt an additional component or modify PID structure in software packages and hardware modules. To prevent impulse signal, a low-pass filter or a modified PID structure is used. However, these methods cannot completely remove the impulse signal. Moreover, the changed PID structure is difficult to analyze quantitatively using standard techniques for the stability and robustness analysis. To prevent the integrator windup, the control action is reduced by conditional integration, back-calculation, etc., in industrial processes [2,4,6]. However, these techniques will suffer from the presence of a significant dead time in the process, which requires an extra tuning effort.

The idea of fuzzy logic control (FLC) was originally introduced [7] and applied in an attempt [8] to control systems that are structurally difficult to model. Since then, FLC has been an extremely active and fruitful research area with many industrial applications reported [9,19,20]. The structure of fuzzy system can be classified according to different applications [10,11]. The majority of applications belong to the class of fuzzy PID controllers [13]. There are too many variations of fuzzy PID controllers, such as, one-input, two-input and three-input PID type fuzzy controllers [13]. In general, there is no standard benchmark. The one-input may miss more information on the derivative action and the three-input fuzzy PID controllers may cause exponentially growth of rules. The two-input fuzzy PID, as we used in the paper, has a proper structure and the most practical use, and thus is the most popular type of fuzzy PID used in various research and application. The system design of the two-input fuzzy PID controller is given in [14,15]. As the knowledge base conveys a general control policy, it is preferred to keep the member function unchanged and to leave the design and tuning exercises to scaling gains. The classical control theory can be used for the gain design [14–16]. There are still lots rooms for research in this aspect.

Motivated by previous discussion, an inherent saturation of fuzzy PID controller is revealed in this paper, and derived from the finite fuzzy rules. The bandwidth of the control system can be adjusted by the parameter of the saturation. The gain of fuzzy PID controller is smaller than that of conventional PID controller due to the inherent saturation. Without the additional filter or the structure modification, the fuzzy PID controller has an inherent

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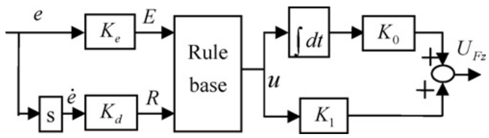

Fig. 1. Structure of the fuzzy-PID controller.

capability to prevent impulse signal. Under the input saturation, the fuzzy PID controller still performs well without the additional anti-windup structure. The fuzzy PID controller is applied to an integrated circuit curing process. Through the simulations and experiments, all these discoveries have been confirmed that will further explain the robustness of the fuzzy PID controller.

2. Problem formulation

2.1. PID controller

The ideal PID controller is described by the following time model [1,2]

$$U_{PID} = K_P\left(e + \frac{1}{T_i}\int e\ dt + T_d\dot{e}\right) \quad (1)$$

where U_{PID} is the control signal acting on the error signal e, K_P is the proportional gain, T_i and T_d are integral time constant and derivative time constant, respectively.

2.1.1. Preventing impulse signal

In order to prevent impulse signal, an additional low-pass filter is often used in most of PID software packages and hardware modules. The transfer function of (1) with an additional low-pass filter is given as [2,12]

$$G_{PID}(s) = \frac{U_{PID}(s)}{E(s)} = K_P\left(1 + \frac{1}{T_i s} + \frac{T_d s}{1 + T_d s/\rho}\right) \quad (2)$$

where $U_{PID}(s)$ and $E(s)$ are Laplace transformation of U_{PID} and e, respectively; ρ is a constant factor with $\rho \in [8,20]$ [1]. However, this low-pass filter can't completely remove impulse derivative signals caused by sudden changes of the setpoint or disturbance.

2.1.2. Anti-windup

In order to prevent integrator windup, the anti-windup strategy is to reduce the control action using conditional integration, back-calculation, etc., when input saturation exists in industrial processes [1,3,4,6]. However, these techniques can suffer from the presence of a significant dead time in the process or, to deal with processes with different normalised dead times, they might require an extra tuning effort, which is undesirable for industrial regulators.

2.2. Fuzzy PID controller

The design of a fuzzy PID controller was discussed in [14] and [15]. Here, only the structure of a fuzzy PID controller is shown in Fig. 1, which combines the features of both fuzzy-PD and the fuzzy-PI controller. Only one two-dimensional rule base is used, which is normally chosen as a linear rule base [17,18] similarly as shown in Table 1, where the linguistic labels are negative large (NL), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM), positive large (PL). The standard triangular membership functions (MFs) are used.

When there are infinite rules, the output model of the rule base is given as follows [14]

$$u = kB(1-\gamma) + \frac{B}{A}\gamma\sigma \quad (3)$$

Table 1
Fuzzy rule base in finite rules.

R/E	NL	NM	NS	ZR	PS	PM	PL
PL	ZR	PS	PM	PL	PL	PL	PL
PM	NS	ZR	PS	PM	PL	PL	PL
PS	NM	NS	ZR	PS	PM	PL	PL
ZR	NL	NM	NS	ZR	PS	PM	PL
NS	NL	NL	NM	NS	ZR	PS	PM
NM	NL	NL	NL	NM	NS	ZR	PS
NL	NL	NL	NL	NL	NM	NS	ZR

$$\sigma = E + R = K_e e + K_d\dot{e} = K_e(e + \alpha\dot{e}) \quad (4)$$

where $K_e = 1/|\max(e)|$, $E = K_e e = iA + e^*$, $R = K_d\dot{e} = jA + r^*$, $k = i + j + 1$, $K_d = \alpha K_e$, $K_1 = \beta K_0$, γ is a nonlinear time-varying parameter $(2/3 \le \gamma \le 1)$, $A = B = 1/3$ are half of the support of each input and out member function respectively, e^* and r^* are relative input data in the inference cell $IC(i,j)$, and k is an index number depending on the inference cell under use. Thus, the mathematical model of the fuzzy PID controller can be easily derived as

$$U_{Fz} = K_0\int u\ dt + K_1 u = K_0\left(\int u\,dt + \beta u\right) \quad (5)$$

where u is described in (3).

Practically, rules are always finite in real-world application as show in Table 1, which clearly shows the bounded effect.

3. Inherent saturation

An inherent saturation model will be derived from the finite rule base. The fuzzy PID controller will be compared with the conventional PID controller, and stability analyzed based on the saturation.

3.1. Saturation analysis

Since finite rules are used, the rule base is bounded. So u in (3) should be changed to include both saturated and non-saturated effects as follows

$$u = sat(\sigma) = \begin{cases} sgn(\sigma) & |\sigma| > 1 \\ g(\sigma) & |\sigma| \le 1 \end{cases} \quad (6)$$

where $g(\sigma)$ is a nonlinear function that is described as follows

$$g(\sigma) = kB(1-\gamma) + \frac{B}{A}\gamma\sigma \quad (7)$$

Combining (6) and (4), (7) becomes

$$g(\sigma) = \frac{B}{A}\sigma + \frac{B}{A}(1-\gamma)(kA - \sigma) = \frac{B}{A}\sigma + \frac{B}{A}(1-\gamma)(A - e^* - r^*) \quad (8)$$

Consider frequency description of (4)

$$\tilde{\sigma}(s) = K_e(1 + \alpha s)E(s) \quad (9)$$

where $\tilde{\sigma}(s)$ and $E(s)$ are Laplace transformation of σ and e, respectively.

Integrating (6), (8) and (9), the equivalent structure of the rule base is shown in Fig. 2.

By substituting $s = j\omega$ into (9), one obtains

$$|\tilde{\sigma}(j\omega)| = E_0\sqrt{1 + (\alpha\omega)^2} \quad (10)$$

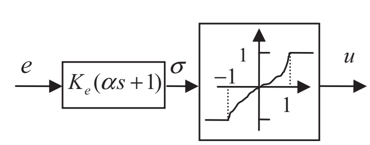

Fig. 2. Equivalent structure of the rule base.