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Pole-placement self-tuning control of nonlinear Hammerstein system and its application to pH process control

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A B S T R A C T

By taking advantage of the separation characteristics of nonlinear gain and dynamic sector inside a Hammerstein model, a novel pole placement self tuning control scheme for nonlinear Hammerstein system was put forward based on the linear system pole placement self tuning control algorithm. And the nonlinear Hammerstein system pole placement self tuning control (NL-PP-STC) algorithm was presented in detail. The identification ability of its parameter estimation algorithm of NL-PP-STC was analyzed, which was always identifiable in closed loop. Two particular problems including the selection of poles and the on-line estimation of model parameters, which may be met in applications of NL-PP-STC to real process control, were discussed. The control simulation of a strong nonlinear pH neutralization process was carried out and good control performance was achieved.

1. Introduction

Since Wellstead and Zarrop put forward the pole-placement self-tuning control method of linear system [1], lots of research work had been done for it [2,3]. Up to now, the pole-placement self-tuning control theory of linear system has been developed well, and it has achieved some successful applications in the control of chemical reactor [4], distillation column [5], boiler, furnace, ultrasonic motor [6] and so on. At the same time, lots of theoretical analysis on the pole-placement self-tuning control algorithms of linear system has been carried out.

However, the linear pole-placement self-tuning control algorithm has only a little adaptability to mild nonlinear systems. Its control performance will be much deteriorated [7] when it is applied to the control of strong nonlinear systems commonly encountered in chemical production processes [8].

A Hammerstein model consists of a static nonlinear sector followed in series by a linear dynamic element. It corresponds to processes with linear dynamics but a nonlinear gain, and it can adequately represent many of the nonlinearities commonly encountered in industrial processes such as pH neutralization processes [9,10]. The Hammerstein model is particularly useful in representing the nonlinearities of a process without introducing the complications associated with general nonlinear operators. Due to the static nature of its nonlinearity, this static nonlinearity can be effectively removed from the control problem, allowing to easily extend linear control algorithms to nonlinear Hammerstein systems [11,12]. Anbumani had proposed an adaptive minimum variance control algorithm for nonlinear Hammerstein system [13], but its application was much limited due to the fact that it was unsuitable for non-minimum phase system and also it required large range fluctuation of control actions.

In this paper, through utilizing the separation characteristics of nonlinear gain and dynamic sector inside a Hammerstein model [11,12], a novel pole placement self tuning control scheme for nonlinear Hammerstein system was put forward based on the linear system pole placement self tuning control algorithm [1–3]. Then, the nonlinear Hammerstein system pole placement self tuning control (NL-PP-STC) algorithm was presented in detail. The identification ability of its parameter estimation algorithm of NL-PP-STC was analyzed, which was always identifiable in closed loop. Two particular problems including the selection of poles and the on-line estimation of model parameters, which may be met in applications of NL-PP-STC to real process control, were discussed. Finally, the control simulation of a strong nonlinear pH neutralization process was carried out and good control performance was achieved.

2. NL-PP-STC Principle and Algorithm

2.1. Hammerstein model

The structure of a Hammerstein model is illustrated in Fig. 1 and it could be described by Eqs. (1) and (2).

$$A\left(z^{-1}\right)y(k) = z^{-d}B\left(z^{-1}\right)x(k) + C\left(z^{-1}\right)e(k) \tag{1}$$

$$x(k) = \sum_{i=1}^{p} r_i u^{i(k)} \tag{2}$$

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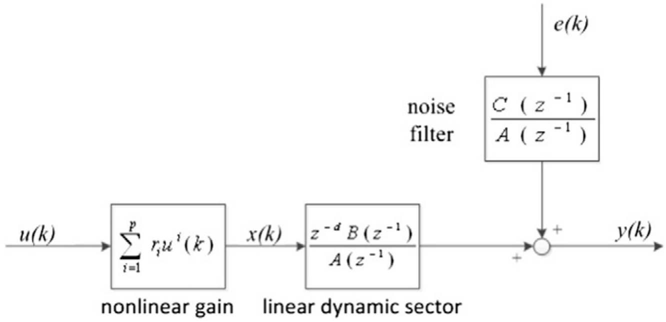

Fig. 1. Structure of a Hammerstein model.

where $A(z^{-1}) = 1 + a_1z^{-1} + a_2z^{-2} + \cdots + a_{n_a}z^{-n_a}$, $B(z^{-1}) = b_1z^{-1} + b_2z^{-2} + \cdots + b_{n_b}z^{-n_b}$, $C(z^{-1}) = 1 + c_1z^{-1} + c_2z^{-2} + \cdots + c_{n_c}z^{-n_c}$, $u(k)$ is the system input, $y(k)$ is the system output, $x(k)$ is the intermediate variable, $e(k)$ represents the white noise, p, n_a, n_b and n_c are the model orders, d is the delay time, $r_i(i = 1, 2,\cdots,p)$ and $a_i(i = 1, 2,\cdots,n_a)$,$b_i(i = 1, 2,\cdots,n_b)$ and $c_i(i = 1, 2,\cdots,n_c)$ are model parameters.

2.2. Pole placement control principle of Hammerstein system

The principle of pole placement for Hammerstein system is presented in Fig. 2 according to the general pole placement control requirements and the characteristics of Hammerstein model [9–14].

In Fig. 2, in order to transfer the nonlinear system pole placement control problem into a more simple linear system pole placement control problem, the nonlinear compensation sector $\frac{1}{\sum_{i=1}^{\hat{p}} \hat{r}_i u^{i(k)}}$ is used to compensate the nonlinear gain $\sum_{i=1}^{p} r_i u^{i(k)}$ of the Hammerstein system. $y_r(k)$ is the set point value and $x'(k)$ represents the intermediate variable. The three sectors $H(z^{-1})$, $\frac{1}{F(z^{-1})}$ and $G(z^{-1})$ are used to assign the system poles to the desired points, which can be taken as:

$$
\begin{aligned}
F(z^{-1}) &= f_0 + f_1z^{-1} + f_2z^{-2} + \cdots + f_{n_f}z^{-n_f} \\
G(z^{-1}) &= 1 + g_1z^{-1} + g_2z^{-2} + \cdots + g_{n_g}z^{-n_g} \\
H(z^{-1}) &= h_0 + h_1z^{-1} + h_2z^{-2} + \cdots + h_{n_h}z^{-n_h}
\end{aligned}
$$

where n_f, n_g and n_h are the orders of $F(z^{-1})$, $G(z^{-1})$ and $H(z^{-1})$, $f_i(i = 0, 1,\cdots, n_f)$, $g_i(i = 1, 2,\cdots, n_g)$ and $h_i(i = 0, 1, 2,\cdots, n_h)$ are parameters.

2.3. Pole placement control algorithm of Hammerstein system

2.3.1. When model is known

Suppose Hammerstein model is already known and then taking $\hat{p} = p$, $\hat{r}_i = r_i(i = 1, 2, \cdots, p)$ the system output can be obtained from Fig. 2.

$$
\begin{aligned}
y(k) = &\frac{F(z^{-1})C(z^{-1})}{A(z^{-1})F(z^{-1}) + z^{-d}B(z^{-1})G(z^{-1})}e(k) \\
&+ \frac{z^{-d}H(z^{-1})B(z^{-1})}{A(z^{-1})F(z^{-1}) + z^{-d}B(z^{-1})G(z^{-1})}y_r(k).
\end{aligned} \tag{3}
$$

It is supposed by pole placement that

$$
\frac{y(k)}{e(k)} = \frac{Q(z^{-1})}{P(z^{-1})} \tag{4}
$$

where $Q(z^{-1})$ and $P(z^{-1})$ is a polynomial of z^{-1}. In order to make the calculation simple, let $Q(z^{-1}) = F(z^{-1})$. Combining Eqs. (3) and (4) can get Eq. (5).

$$
A(z^{-1})F(z^{-1}) + z^{-d}B(z^{-1})G(z^{-1}) = P(z^{-1})C(z^{-1}). \tag{5}
$$

Making the corresponding coefficients of power of z at both sides of Eq. (5) equal, a group of linear equations could be achieved. Furthermore, take $n_f = n_b + d$, $n_g = n_a$, $n_p \le n_a + n_b - n_c + d$ (here n_p is the order of $P(z^{-1})$), the only real root of $f_i(i = 0,1,\ldots,n_f)$ and $g_i(i = 1,2,\ldots,n_g)$ could be found, and then $F(z^{-1})$ and $G(z^{-1})$ could be achieved.

Substituting Eq. (5) into Eq. (3), we have

$$
\frac{y(k)}{y_r(k)} = \frac{z^{-d}H(z^{-1})B(z^{-1})}{P(z^{-1})C(z^{-1})}. \tag{6}
$$

In order to assign the closed loop poles of system output to set point value at $P(z^{-1})$, and make the system output have no steady state offset, we can take

$$
H(z^{-1}) = \frac{C(z^{-1})\left[P(z^{-1})|_{z=1}\right]}{\left[B(z^{-1})|_{z=1}\right]} \tag{7}
$$

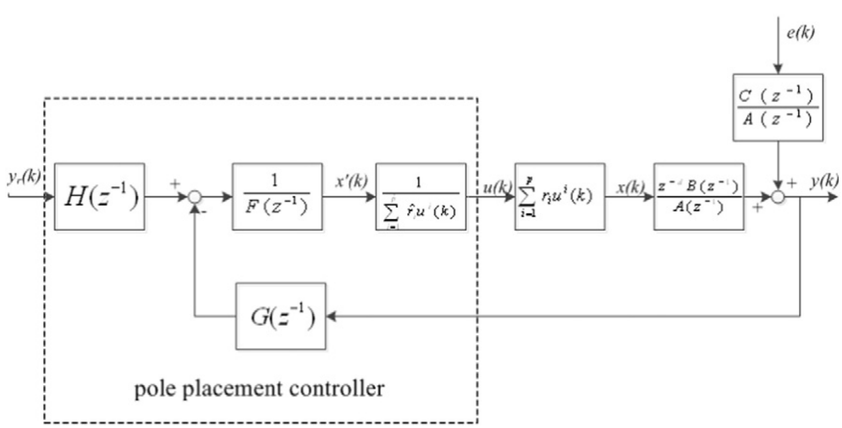

Fig. 2. Scheme of Hammerstein system pole-placement control.