Fifth IFSA World Congress (1993), 1106-1108

# Fuzzy Learning Control: Application to an Industrial Polymerization Reactor

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**ABSTRACT:** This paper deals with an industrial application of a fuzzy feedback combined learning control to an industrial batch free radical polymerization reactor. As a result, the plant has reduced the batch reaction time by 50 minute and stabilized both by 40 percent reduction of the standard deviations of product qualities, such as the total solid content and the graft gum, and by 45 percent reduction of the standard deviation of the batch reaction end time.

## Introduction

One of the major characteristics of a batch free radical polymerization reactor is to track a predetermined setpoint trajectory repeatedly over a batch-wise operation. During the operation, the process will vary and sometimes show nonlinearities. If the process is completely known, an appropriate input for the predetermined setpoint trajectory can be obtained from a nonlinear variable or output transformation. However, due to the lack of on-line measurements of reaction rate, the existence of the unknown system characteristics inherent to the reaction kinetics such as reaction heat, reaction rate and volumetric change over the operating range, and the non-steady state operation over the range, it is hard to find the process model either from first principles or from black box identifications. Since both the fuzzy control and the learning control are able to apply such a process which is hard to determine the full description of the process dynamics, their combined scheme can be an attractive and practical tool for temperature control of a batch polymerization reactor.

In this study, a perfect control input is derived from the nonlinear variable transformation of the energy balance equations around the reactor. From the analysis of the perfect input, a new control strategy is proposed: a fast fuzzy algorithm (FFA) is applied to a measurable part as a feedback controller, and a learning control to an unmeasurable part, which the error is reduced recursively as the learning operation continues.

## The nonlinear variable transformation

The control problem of the batch process is to keep the reactor temperature constant by regulating the cooling medium temperature in the reactor jacket. The major disturbance in the reactor is the reaction heats which varies according to the conversion rate over the batch time.

The energy balances around the reactor and reactor jacket are expressed by

$$\begin{aligned}\frac{dT_r}{dt} &= f_1(T_r, T_j)\\ &= \frac{1}{\tau_1}(-T_r + T_j + q)\end{aligned} \tag{1}$$

$$\begin{aligned}\frac{dT_j}{dt} &= f_2(T_r, T_j, W_j)\\ &= \frac{1}{\tau_2}(T_r - T_j + aT_jW_j - bW_j)\end{aligned} \tag{2}$$

Since the bilinear variable, $T_jW_j$, in equation (2) will vary over the batch time, it is hard to determine a linearization point. To get a control input, new coordinates $x_1$, $x_2$ and the new control signal $u$ have been introduced by

$$\begin{aligned}&x_1 \triangleq T_r \;;\quad x_2 \triangleq \frac{dT_r}{dt}\;;\\ &u \triangleq \frac{\partial f_1}{\partial T_r}f_1 + \frac{\partial f_1}{\partial T_j}f_2\end{aligned} \tag{3}$$

These transformations result in the linear system, and the desired response of $T_r$ to the command signal is given by

$$G_d(s) = \frac{1}{p_1s^2 + p_2s + 1} \tag{4}$$

Solving these equations for $W_j$ gives the desired feedback.

$$\begin{aligned}W_j = &\frac{K_C}{T_j-T_{CW}}\left[(T_r^d-T_r) - \tau_D\frac{dT_r}{dt}\right]\\ &+\frac{T_j-T_r^d}{a(T_j-T_{CW})} + \frac{K_L}{T_j-T_{CW}}\frac{\partial q}{\partial T_r}\frac{dT_r}{dt}\end{aligned} \tag{5}$$

$$\text{where,}\quad \begin{aligned}K_C &= \frac{\dfrac{\tau_1\tau_2}{p_1} - \left(\dfrac{\partial Tr}{\partial Tj} - 1\right)}{a\left(\dfrac{\partial Tr}{\partial Tj} - 1\right)}\\ \tau_D &= \frac{\dfrac{p_2}{p_1} + \dfrac{1}{\tau_1}\left[-1\,\dfrac{1}{\dfrac{\partial Tr}{\partial Tj}}\right]}{\dfrac{1}{p_1} - \dfrac{1}{\tau_1\tau_2}\left(\dfrac{\partial Tr}{\partial Tj} - 1\right)}\\ K_L &= \frac{\tau_2}{a\left(\dfrac{\partial Tr}{\partial Tj} - 1\right)}\end{aligned}$$

Since the reaction heat, $q$, is hard to measure in a real field, $\partial q/\partial T_r$ in equation (5) makes the above feedback impractical. The right hand side of equation (5) has two parts: the PD type control and the feedforward control which have all measurable variables but unknown parameters; the last term which has an unmeasurable variable, $q$.

## The proposed control scheme

Examining equation (5) leads us a control scheme consisting of two parts: the one is a fuzzy control which covers the feedback and the feedforward part; the other is a learning control for the unmeasurable and unknown term.

### The fast fuzzy algorithm

Under the conditions that a crisp input value is treated as a fuzzy singleton and the membership functions are any type of continuous equations, the direct fuzzy algorithm is expressed in simple relations

$$\alpha_i = f_i(x^*) \tag{6}$$

$$M_i = g_i(\alpha_i)\cdot M^\circ_i \tag{7}$$

where $x^*$ is the crisp input value, $f_i$ is the antecedent membership function and $g_i$ is the transformed consequent function, respectively; $\alpha_i$ is the weighting factor; $M_i$ and $M^\circ_i$ are the support values of which $\alpha_i$ is less than 1 and is equal to 1, respectively, with $i = 1,2,\cdots,n$.

Since $M^\circ_i$ is independent of $\alpha_i$ in equation (7), $g_i(\alpha_i)$ can be transformed into equation (6) and the results are given by

$$\beta_i = g_i\{f_i(x^*)\} \tag{8}$$

$$M_i = \beta_i\cdot M^\circ_i \tag{9}$$

where $\beta_i$ is the transformed weighting factor. Equations (8) and (9) show the basic concept of the fast fuzzy algorithm that is using an equivalent crisp function for the consequence. Takagi and Sugeno

(1985) have proposed a similar concept of using a linear function instead of the consequence. However, the different point is that FFA uses not the intuitive linear function but the transformed function of the direct reasoning methods.

### The learning controller

We proposed a predictive 3-mode learning algorithm (1993) which is expressed by

$$U_{i+1}^{L}(k) = U_i(k) + \frac{P(q^{-1})}{L(q^{-1})}\left(Y^{d}(k+PH) - Y_i(k+PH)\right) \tag{10}$$

where $U(k)$ and $Y(k)$ designate the manipulated variable and the controlled variable at sampling instant $k$, respectively; $P(q^{-1})/L(q^{-1})$ is the 3-mode learning controller described by the backward shift operator; $PH$ designates the prediction horizon; subscript $i$ indicates the $i$th repetitive operation; superscript $L$ and $d$ stand for learning and desired, respectively.

In this application, the learning algorithm is applied only for the initial heat-up stage because the predetermined reactor temperature trajectory is in an open-loop control after the initiator charged. And it is found that the proposed algorithm is same as BP's method (Arimoto and his colleagues, 1984 and 1988) and Lee's method (Lee et al., 1991), because the simplified process model of the initial heat up stage obtained from plant data is first order without time delay.

### Conclusion

A fuzzy feedback combined learning control is proposed for the control problem of repetitive unit operations. The control strategy of a batch reactor has been obtained by analyzing the perfect input derived from the nonlinear variable transformation. For the feedback action on the measurable part, the fast fuzzy algorithm is applied over the whole batch operation period, and for the unmeasurable but repeated part, the learning algorithm is applied to the stabilization of the initiator charge condition. The proposed scheme has applied to an industrial batch free radical polymerization reactor. It is found that the proposed combined control scheme leads the plant to increase the productivity by 10 percent and reduce both the standard deviation of the product qualities by 40 percent and that of the batch reaction end time by 45 percent.

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