PID Control of Poly-butadiene Latex(PBL) Reactor Based on Closed-loop Identification and Genetic Algorithm

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Abstract

The PBL (Poly-butadiene Latex) production process is a typical batch process. Changes of the reactor characteristics due to the accumulated scaling with the increase of batch cycles require adaptive tuning of the PID controller being used. In this work we propose a tuning method for PID controllers based on the closed-loop identification and the genetic algorithm (GA) and apply it to control the PBL process. An approximated process transfer function for the PBL reactor is obtained from the closed-loop data using a suitable closed-loop identification method. Tuning is performed by GA optimization in which the objective function is given by ITAE for the setpoint change. The proposed tuning method showed good control performance in actual operations.

1. Introduction

Although several advanced control strategies have been developed, structurally simple proportional-integral-derivative (PID) controller is still widely used in industrial control systems[1]. The use of PID control algorithms in various application fields stems from the facts that include the PI or PID controller structure is simple and its principle is easy to understand; the performance of the PID control is robust and acceptable in a wide range of applications. Tuning of PID controllers has attracted concerns of many researchers. If the target process approximates to the first or second order model, the tuning parameters can be obtained by the Ziegler-Nichols (Z-N), Cohen-Coon, ITAE (Integral of the Time-weighted Absolute Error) and IMC (Internal Model Control) methods[2]. Sung *et al.*[3] derived analytical derivative formulas that enable to compute optimal tuning parameters for the anti-derivative-kick PID controller based on the well-known Levenberg-Marquardt optimization method. Chen and Seborg[4] studied a design method for PID controllers based on the direct synthesis approach and specification of the desired closed-loop transfer function for disturbances.

So far tuning of PID controllers has relied mainly on open-loop analysis. But usually the open-loop test is prohibited in operating plants and disturbances and noises may cause unexpected control errors during closed-loop operation. For these reasons closed-loop identification has attracted much attention[5,6]. Pramod and Chidambaram[7] calculated the transfer function using the closed-loop identification for the bioreactor controlled by a PID controller. They assumed the target process to be the FOPTD (First-Order Plus Time-Delay) model and did not consider noises in the closed-loop identification.

The PBL(Poly-butadiene Latex) process considered in the present study is a typical nonlinear batch process and is controlled by PID controllers in cascade control structure. As operation batches proceed, dynamics of the process change and the control performance is getting worse. But PID controllers with fixed tuning parameters are used during the whole operation cycle. For this reason consistent product quality could not be achieved and the number of batches in one operation cycle was limited only to 44 ~ 47. Increase of the number of batches in one operation cycle while maintaining the product quality as desired is imperative to enhance the economics of the plant.

In the present study, we propose a tuning method for PID controllers and apply the method to control the PBL process in LG chemicals Co. located in southwestern area of Korean peninsula. In the tuning method, we first find the approximated process model after each batch by a closed-loop identification method using operating data and then compute optimum tuning parameters of PID controllers based on GA (Genetic Algorithm) method.

2. PBL reactor

Figure 1 shows the schematics of the PBL reactor considered in the present study. Reaction begins with the injection of the reactant (Acrylonitrile butadiene styrene). The heat generated during the reaction is removed by the refrigerant (NH_3) flowing inside the internal tube. The reactor temperature is controlled by adjusting the level of the internal tube. As the operation batch is repeated, the polymer fouling is accumulated on the surface of the internal tube, causing decrease of cooling efficiency and poor control performance.

The control structure of the PBL reactor is a typical cascade control system. The master controller (G_{C1}) determines the setpoint for the slave controller by comparing the present reactor temperature with the setpoint, and the salve controller (G_{C2}) regulates the refrigerant level of the internal tube to control the reactor temperature. In the actual operation, the same tuning parameters are used from the first batch to the last batch resulting in the poor control performance due to the change of reactor dynamics. It is obvious from the operation data that the control performance is getting worse as the operation batch proceeds.

3. Closed-loop Identification

The identification of plant models has traditionally been done in the open-loop mode. The desire to minimize the production of the off-spec product during an open-loop identification test and the unstable open-loop dynamics of certain systems have increased the need to develop methodologies suitable for the system identification.

Open-loop identification techniques are not directly applicable to closed-loop data due to correlation between process input (i.e., controller output) and unmeasured disturbances. Based on Prediction Error Method (PEM), several closed-loop identification methods have been presented by Forssell and Ljung[8]: Direct, Indirect, Joint Input-Output, and Two-Step Methods.

However, these methods require a priori knowledge on the plant order and time delay. And, theoretically, the identifiability can be guaranteed under mild conditions. The newly developed, so-called the open-loop subspace identification method has been proven to be a better alternative to the traditional parametric methods. This is especially true for high-order multivariable systems, for which it is very difficult to find a useful parameterization among all possible candidates.

The subspace identification method has its origin in classical state-space realization theory developed in the 60's. It uses the powerful tools such as Singular Value Decomposition (SVD) and QR factorization. No nonlinear search is performed nor is a canonical parameterization used. There are many different algorithms in the subspace identification field, such as N4SID[9], MOESP[10,11] and CVA[12]. Recently, Ljung and McKelvey[13] investigated the subspace identification method which calculates the state-space model from the closed-loop data. The state can be determined by using SVD. The future outputs are given with future inputs and noises being set to zero.

If the test data sets are gathered from open-loop tests, we can apply the LS method. The solutions are unbiased since the process inputs are uncorrelated with process noise terms. But, if the process input is a function of the process noise as in the closed-loop test, the solutions would be biased. For this reason, application of subspace identification methods for the closed-loop test gives biased estimation results regardless of the accuracy of the next steps. This is the main problem in the application of the subspace identification method for the closed-loop system.

We can assume $D = 0$ since most processes have at least one delay between the process output and the process input. It should be noted that the process input $u(k-1)$ is a function of the past process outputs $y(k-m)$, $m = 1,\ 2,\ \cdots,\ na$ for usual feedback controllers and that the process inputs $u(k-m)$, $m = 1,\ 2,\ \cdots,\ nb$ are uncorrelated with $e(k)$. Therefore, if we apply LS method to the ARX model, we can obtain unbiased estimates of states. Subsequent steps for state estimation and the system matrix estimation are exactly the same with those of subspace identification methods. These methods do not require knowledge on the order and the time delay of the process.

The PBL reactor considered in the present study is a typical batch process and the open-loop test is inadequate to identify the process. We employed a closed-loop subspace identification method which is similar to that proposed by Ljung and McKelvey[13]. This method identifies the linear state-space model using high order ARX model.

To apply the linear system identification method to the PBL reactor, we first divide a single batch into several sections according to the injection time of initiators, changes of the reactant temperature and changes of the setpoint profile, etc. Each section is assumed to be linear. The initial state values for each section should be computed in advance. The linear state models obtained for each section were evaluated through numerical simulations.

As for tuning parameters, values used in actual operations were used (the master controller : P=5%, I=1300sec, D=0.2sec, for the slave controller : P=200%, I=3sec, D=0.6sec). Compared with plant operation data, we could see the effectiveness of the model obtained by the closed-loop identification method.

4. Genetic tuning of PID controllers

The genetic algorithm has attracted attentions of many researchers and found its application especially in optimization studies. The main advantage of the use of the genetic algorithm in optimizations lies in improved possibility of finding the global optimum[14]. In the present study, the ITAE was chosen as the objective function to achieve minimal control errors. Tuning parameters (P, I, D) for the PID controller are obtained by the genetic optimization consisting of selection, mutation and crossover operations.

Optimization methods based on the gradient information such as QP (Quadratic Programming) and SQP (Sequential Quadratic Programming) etc. often reach to local minimum depending on the choice of initial values. Possibility to reach a local minimum increases if we confine the output of the PID controller within a certain range(for example, $0 \sim 100\%$) or if we use a modified PID controller based on the integral anti-windup or anti-derivative-kick technique. For this reason GA (Genetic Algorithm) is our choice for the optimization. Details on GA can be found elsewhere[14]. Determination of PID tuning parameters by GA can be summarized as following:

Step 1. Created the initial population for tuning parameters (P, I, D).

Step 2. Calculate ITAE for step response using closed-loop control system about the approximated process model ($\hat{G}_P$).

Step 3. If the criteria are satisfied, stop computation. If not, go to the next step.

Step 4. Select of superior chromosomes that have low ITAE value.

Step 5. Create the new population (P, I, D) using crossover/mutation.

Step 6. Compute the ITAE value for the closed-loop control system based on the results of step 5 and go to step 3.

5. Results and Discussions

In the present work only the tuning parameters of the master controller are considered. The process model is identified based on the operation data of 35th batch for illustration. The operation data of any other batch can be used and identification and tuning after each batch would be most desirable. The computation time is 2 minutes on the platform based on the Pentium 5, which is quite acceptable for on-line application considering the cleaning and charging time of 20 minutes. On-line identification and tuning after each batch is planned in the plant. In the PBL plant considered in the present study, there are 11 PBL reactors and among them two reactors (reactor A and reactor B) were selected for the test application. The 3rd column shows the controller parameters being used in actual operations. The 4th, 5th and 6th column show the values of tuning parameters obtained from the closed-loop identification and GA optimization based on the operation data of 1st, 26th and 35th batch respectively. Values in the 7th column are the average values of the previous three columns and are used in the 10th batch of the reactor A and 16th batch of the reactor B. Nonconsistent values of P, I and D indicate that the master controller should be tuned after each batch.

Figure 2 shows results of operations of the reactor A. Figure 2(a) shows the results of operation at 9th batch with the parameters without tuning, i.e., the parameters used in the 1st batch are still being used. Figure 2(b) shows the results of operation at 10th batch with the parameters tuned by the closed-loop identification and GA optimization method. As can be seen, oscillations are suppressed and the movement of the valve is more stabilized. For comparison, the parameters used in the 9th batch were used again in the

11th batch. From Figure 2, we can see clear improvement of the control performance with the use of GA tuning method.

Figure 3 shows results of operations of the reactor B. Figure 3(a) shows the results of operation at 15th and 17th batches respectively without tuning, i.e., the parameters used in the 1st batch are still being used. By tuning the parameters based on the closed-loop identification and GA method as before, we could achieve better control performance (Figure 3(b)).

6. Conclusions

The closed-loop identification and GA optimization were used to tune the parameters of the PID controller used in the PBL (Poly-butadiene Latex) reactor. The one cycle of operation consists of 44 – 47 batches. We first identify the model of the PBL reactor by the closed-loop identification followed by the determination of PID parameters using the GA optimization method. The process model is identified based on the single batch operation data for illustration. The operation data of any batch can be used and identification and tuning after each batch would be most desirable. The computation time is 2 minutes on the platform based on the Pentium 5, which is quite acceptable for on-line application considering the cleaning and charging time of 20 minutes. On-line identification and tuning after each batch is planned in the plant. The proposed tuning method showed good control performance in actual operations.

Nomenclature

A, B, C, D = n-dimensional system matrixs
CVA = canonical variate analysis
e = white noise
GA = genetic algorithm
G_C = transfer function of the controller
G_P = transfer function of the process
$\hat{G}_P$ = transfer function of the approximated process
ITAE = integral of the time-weighted absolute error
K = matrix of kalman gain
K_C = controller gain
K_{cu} = ultimate gain
MOESP = multivariable output-error state space identification
N4SID = numerical algorithms for subspace state space system identification
PID = proportional-integral-derivative controller
R = reference signal
t = time [sec]
u, U = process input or controller output
x = n-dimensional state vector
y, Y = process output

<Greek letters>

ρ = residual
τ_i = integral time of the controller
τ_d = derivative time of the controller

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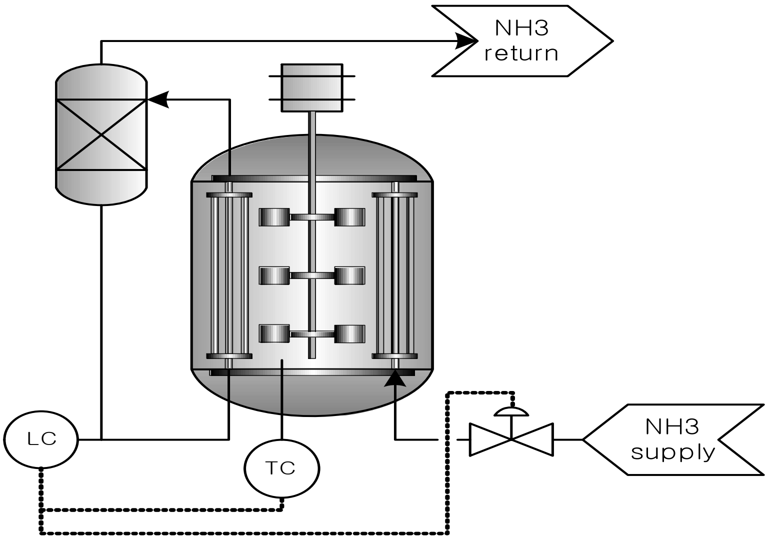

Figure 1. Schematics of the PBL batch reactor

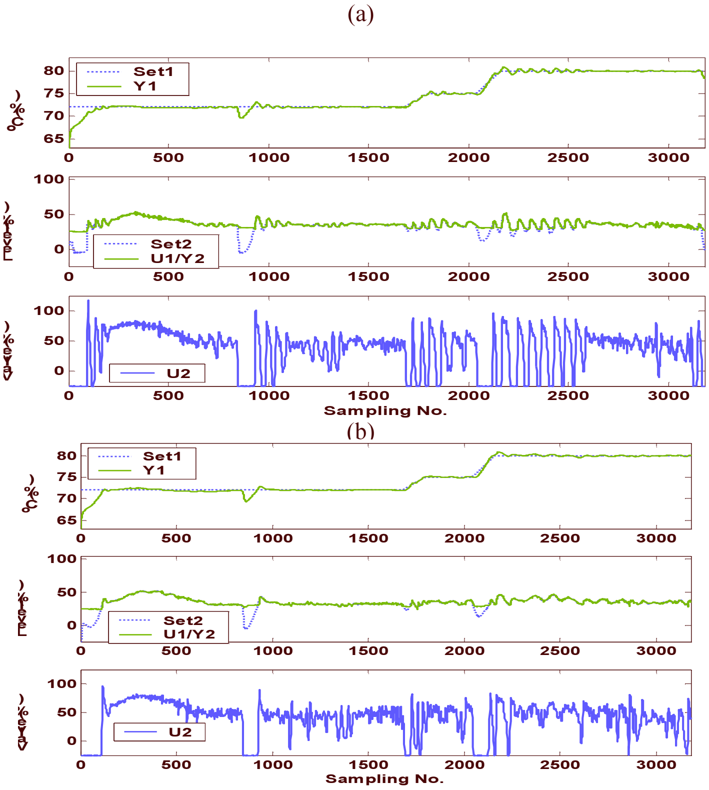

Figure 2. Results of closed-loop operations (reactor A):
(a) 9th batch: without tuning, (b) 10th batch: GA tuning

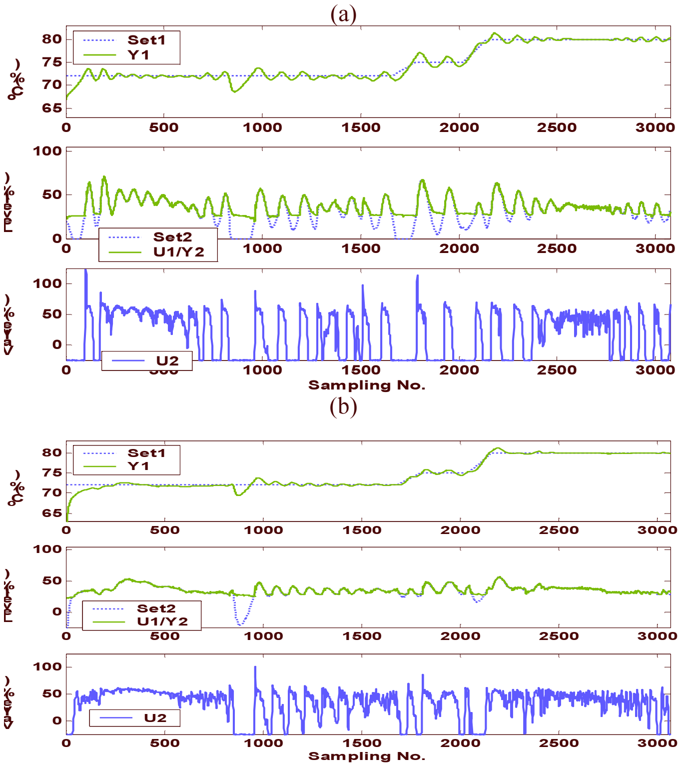

Figure 3. Results of closed-loop operations (reactor B):
(a) 15th batch: without tuning, (b) 16th batch: GA tuning