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Development of batch proportional-integral-derivative controller

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Abstract−Previous batch control methods, such as iterative learning control (ILC) or run-to-run (R2R) control, can significantly improve the control performance of the batch process. However, to guarantee the expected good control performance, a fairly accurate process model is required for these controllers. Also, the implementation is numerically complicated so that it is difficult to be applied to real manufacturing processes. To overcome these problems, a new batch proportional-integral-derivative (PID) control method is proposed, which borrows the concept of the conventional PID control method. Simulation studies confirm that the proposed method shows acceptable performance in tracking a setpoint trajectory, rejecting disturbances, and robustness to noises and variation of process dynamics. The application to the commercial batch process of a single crystal grower verifies that the proposed method can significantly contribute to improving the control performances of real batch processes.

Keywords: Batch Process, Batch Controller, Batch PID Controller, Feed Forward Controller, Czochralski Process

INTRODUCTION

Batch processes have been widely used in various industrial fields such as chemical production, mechanical machining, and semiconductor manufacturing. The precise control of these batch type processes can much contribute to improving the productivity, quality of the product and saving utilities and raw materials [1]. Until now, advanced batch-wise control methods such as iterative learning control (ILC) and run-to-run (R2R) control [2,3] have been developed to enhance the control performance of batch processes and implemented in various areas [4-7].

However, since the above-mentioned batch control methods are basically open-loop control within a batch from the time-wise point of view, they are not able to effectively manipulate batch-wise irregular disturbances. To overcome this, many researchers suggested batch controllers combined with time-wise feedback controllers such as proportional-integral-derivative (PID) control and model predictive control (MPC) [8-11]. The two-stage approach (time-varying feedback control and batch-varying feedforward control) can significantly improve the control performance of the batch process compared with the case that only usual feedback controllers are used.

But, a fairly accurate process model is required for the previous batch controllers to guarantee the expected good control performance. Sometimes, it is hard to obtain an accurate process model in industrial environments that uncertainty such as disturbances and noises are too big compared to the test signal, or the operation does not allow the engineer to excite the process enough for the process data to be sufficiently informative for the acceptable process identification. Also, the implementation of the previous model-based batch controller is not easy because the inverse problem of the process model and/or an optimization problem should be solved.

In this research, a batch proportional-integral-derivative (PID) controller is proposed to circumvent the problems of the previous batch control methods of ILC and R2R. The proposed method is an extension of the conventional feedback PID controller to be applicable to batch processes, securing the advantages of the conventional PID controller such as simplicity, robustness, easy and intuitive tuning and no accurate process model required. Simulation studies confirm that the proposed batch PID controller shows acceptable control performance in tracking various setpoint trajectories and rejecting various disturbances and good robustness to uncertainties such as noises and variation of the process dynamics. Also, application study on a real single crystal grower process proves that the proposed method can significantly contribute to improving the control performance of real batch processes.

CONVENTIONAL FEEDBACK PID CONTROLLER

Before deriving the proposed batch PID controller with borrowing the concept of the conventional PID control for continuous processes, let us briefly examine the basic concept of the conventional feedback PID control, which has been most widely used in industry due to the simplicity, good performance and excellent robustness to uncertainty. The conventional PID controller is a time-wise feedback controller composed of the following three parts of the proportional, integral and derivative part [12]:

$$u_{fb}(t)=k_{c,fb}(y_s(t)-y(t))+\frac{k_{c,fb}}{\tau_{i,fb}}\int_0^t(y_s(\tau)-y(\tau))d\tau + k_{c,fb}\tau_{d,fb}\frac{d(y_s(t)-y(t))}{dt} \qquad (1)$$

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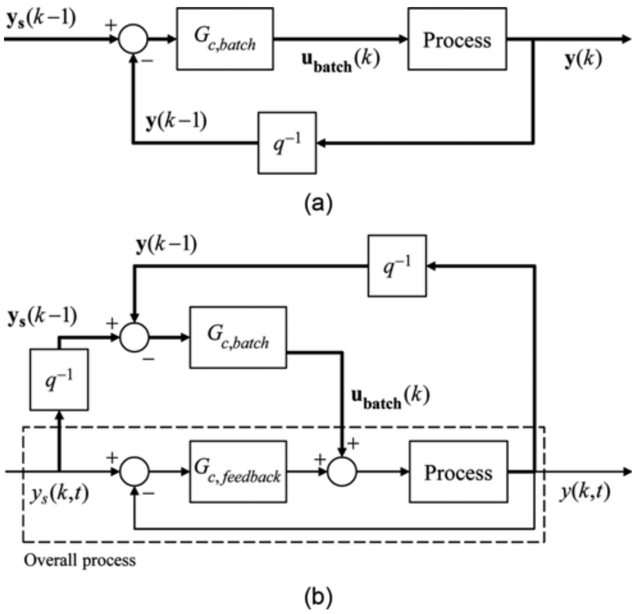

Fig. 1. Two batch control structures: (a) Only batch controller, (b) batch controller combined with a feedback controller.

where, $u_{fb}(t)$, $y_s(t)$, and y(t) are the control output, setpoint, and process output, respectively. The tuning parameters $k_{c,fb}$, $\tau_{i,fb}$, and $\tau_{d,fb}$ are called the proportional gain, integral time and derivative time, respectively. The tuning parameters can be determined by various tuning rules such as trial-and-error, Ziegler-Nichols (ZN), internal model control (IMC), integral of the time-weighted absolute error for the first-order plus time delay process (ITAE-1), or integral of the time-weighted absolute error for the second-order plus time delay process (ITAE-2) [12].

PROPOSED BATCH PID CONTROLLER

The proposed batch PID controller has two types of the control structure illustrated in Fig. 1. The control structure with only the batch PID controller is represented in Fig. 1(a), and Fig. 1(b) is the case that the batch PID controller is combined with a feedback controller. Here, $G_{c,batch}$ and $G_{c,feedback}$ are the batch PID controller and feedback PID controller, respectively. $\mathbf{y}(k-1)$ and $\mathbf{y}_s(k-1)$ denote the process output vector and the setpoint vector, containing the sampled data of the process output and the setpoint of the whole (k−1)-th batch. For example, $\mathbf{y}(k-1)=[y(k-1,0)\ y(k-1,\Delta t)\ \ldots\ y(k-1,(N_{batch}-1)\Delta t)]$ and $\mathbf{u}_{batch}(k)=[u_{batch}(k,0)\ u_{batch}(k,\Delta t)\ \ldots\ u_{batch}(k,(N_{batch}-1)\Delta t)]$, where, Δt and N_{batch} are the sampling time and the number of the samples for one batch. q^{-1} denotes one batch delay. For instance, $\mathbf{y}(k-1)=q^{-1}\mathbf{y}(k)$ and $\mathbf{y}_s(k-1)=q^{-1}\mathbf{y}_s(k)$. y(k, t) and $y_s(k, t)$ denote the process output and the setpoint at the batch time t in the *k*-th batch.

The batch PID controller of Fig. 1 is to calculate the control output of $\mathbf{u}_{batch}(k)$ (that is, all $u_{batch}(k, t)$ for all the samples at t=iΔt, i=0, 1, …, $N_{batch}-1$ in the *k*-th batch) on the basis of the setpoint and process output data ($\mathbf{y}_s(k-1)$ and $\mathbf{y}(k-1)$) of the previous batch and apply $\mathbf{u}_{batch}(k)$ to the batch process in a batch-wise manner. So, the batch controller is a kind of feedforward control. In the proposed control structure, the feedforward control is indicated by a bold line, while the feedback control is demonstrated as a thin line. The purpose of this research was to develop the batch PID controller of $G_{c,batch}$.

1. Batch PID Control

The proposed batch PID controller is described by the following equation:

$$u_{batch,PID}(k)=k_{c,batch}\left(E_{batch}(k-1,t)+\frac{1}{\tau_{i,batch}}\int_0^{k-1}E_{batch}(\tau,t)d\tau+\tau_{c,batch}\frac{dE_{batch}(k-1,t)}{dk}\right) \tag{2}$$

where, $k_{c,batch}$, $\tau_{i,batch}$ and $\tau_{d,batch}$ are the tuning parameters for the proposed batch PID controller. And, $E_{batch}(k, t)$ is the exponential time-weighted moving average error of the *k*-th batch at the batch time t defined as follows:

$$E_{batch}(k,t)=\frac{\int_t^{t+3\tau_w}(y_s(k,\tau)-y(k,\tau))w(\tau-t)d\tau}{\int_t^{t+3\tau_w}w(\tau-t)d\tau} \tag{3}$$

where, w(t) is the weight function and τ_w is the time constant of the weight function. The exponential time-weighted moving average of the future error, $E_{batch}(k, t)$, rather than just the present error is used to calculate the present control output because the pulse signal of the present control output during one sampling time determines all the future process output corresponding to the impulse response of the process. So, it is reasonable that the exponential time-weighted moving average error with the weight of the impulse response is chosen as the control error to be eliminated by the batch PID controller. Because the integration range from t to t+3τ_w can cover almost the area of the error [13], it is selected as the range of integration. A smaller integration range cannot cover the whole area of the error, while a larger integration range inceases the computation load without benefits. As mentioned, the ideal weight function for the proposed batch PID control is the impulse response of the process at the batch time t. But, because it is hard to obtain the exact impulse response of the process, the impulse response of the first order plus time delay (FOPTD) model is used as the weight function in this research as follows:

$$\begin{cases} w(t)=0,\ t<\theta_w \\ w(t)=\dfrac{t-\theta_w}{\tau_w}\exp\left(-\dfrac{t-\theta_w}{\tau_w}\right),\ t\geq\theta_w \end{cases} \tag{4}$$

where, τ_w and θ_w correspond to the time constant and time delay of the FOPTD model, respectively. A low-pass filter is assigned to the control output of the batch PID controller to batch-wisely smoothen the batch control output by weighting the control output ($u_{batch}(k-1, t)$) of the previous batch as follows:

$$u_{batch}(k,t)=\exp\left(-\frac{1}{\tau_l}\right)u_{batch}(k-1,t)+\left(1-\exp\left(-\frac{1}{\tau_l}\right)\right)u_{batch,PID}(k,t) \tag{5}$$

where, τ_l is the time constant of the low-pass filter. $u_{batch}(k, t)$ of Eq.

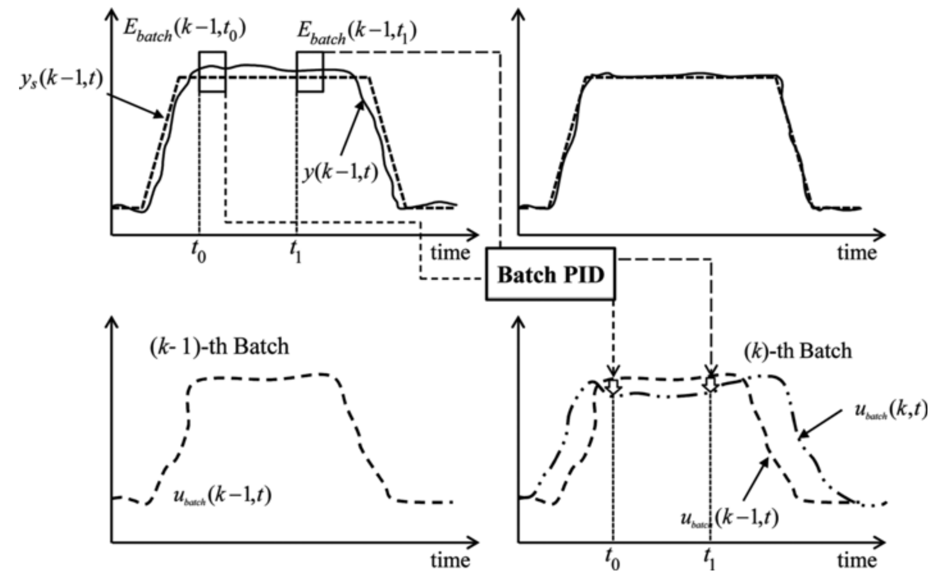

Fig. 2. Conceptual diagram to show how the batch PID controller works.

(5) is the final control output to be applied to the *k*-th batch at the batch time t.

Fig. 2 illustrates the conceptual diagram to show how the proposed batch PID controller works. First, it calculates all the representative control errors ($E_{batch}(k-1, t)$) of the (k−1)-th batch using Eq. (3) for all the samples at t=iΔt, i=0, 1, …, $N_{batch}-1$. And, all the batch control outputs ($u_{batch}(k, t)$) of the (k)-th batch for all the data points are determined by the proposed batch PID logic from Eqs. (2)-(5) and applied to the (k)-th batch to achieve better the control performance of the (k)-th batch than that of the (k−1)-th batch. By repeating this procedure for every batches, the control performance can be improved more and more as the batch number increases.

2. Batch PID Control Combined with Feedback Controller

Most control systems to control the batch process in industry use a feedback control strategy. The feedback control can significantly attenuate the effects of severe disturbances and remove the control error in the setpoint tracking problem. So, the control engineer would prefer a combination form of the feedback controller and the batch controller as shown in Fig. 1(b). The proposed batch control method can be combined with the feedback control system in a straightforward manner because the overall process to be controlled by the batch PID control is structurally the same with the process in the case of Fig. 1(a).

The result of the first batch controlled by only the feedback control without the batch PID controller can be chosen as a good initial trajectory for the integral part of the batch PID controller. After the first batch, the process input (final control output) will be the summation of the two control outputs of the batch PID control of Eqs. (2)-(5) and the feedback PID control of Eq. (1) as follows:

$$u(k, t)=u_{batch}(k, t)+u_{feedback}(k, t) \quad (6)$$

where, $u_{batch}(k, t)$ and $u_{feedback}(k, t)$ are the outputs of the batch PID controller of Eqs. (2)-(5) and the feedback PID controller of Eq. (1) for the k-th batch and the batch time t. u(k, t) is the final control output to be applied to the k-th batch and the batch time t.

The difference between the batch PID control and the conventional PID control is that the batch PID control uses the integral and derivative with respect to the batch number, while the conventional PID control uses the integral and derivative with respect to time. Except for the difference, two the controllers have the same structure so that the principles of removing the offset by the integral part, decreasing the closed-loop response time by the proportional gain and increasing the robustness by the derivative part are still valid to the batch PID control, making the tuning of the batch PID control simple and intuitive and also guaranteeing the advantages such as simplicity, robustness, easy and intuitive tuning and no accurate process model required.

DETERMINATION OF TUNING PARAMETERS

In this section, we discuss how to determine the tuning parameters of the proposed method. First, the process model should be identified and/or reduced to a first-order plus time delay (FOPTD) or second-order plus time delay (SOPTD) model because most PID tuning rules can handle only FOPTD or SOPTD model. Based on the reduced models, the parameters of the feedback PID control can be tuned. ITAE-1 tuning rule for the setpoint tracking combined with the model reduction [12] is used in this paper. After that, the batch PID parameters are tuned as follows: $k_{c, batch}=0.4/a$, $\tau_{i, batch}=1.0$ and $\tau_{d, batch}=0.25$ for the closed-loop case and $k_{c, batch}=0.2/a$, $\tau_{i, batch}=1.0$ and $\tau_{d, batch}=0.25$ for the open-loop case are recommended for the tuning parameters of the batch PID controller. Here, a is the maximum value of the step response of the process. The step response of the open-loop case corresponds to the process output excited by the unit step process input, while that of the closed-loop case is the case excited by the unit step input disturbance. Fig. 3 shows the step response (equivalently, the unit step input response) of the open-loop type batch control case (Fig. 1(a)) and the step response (equivalently, the step input disturbance response) of the

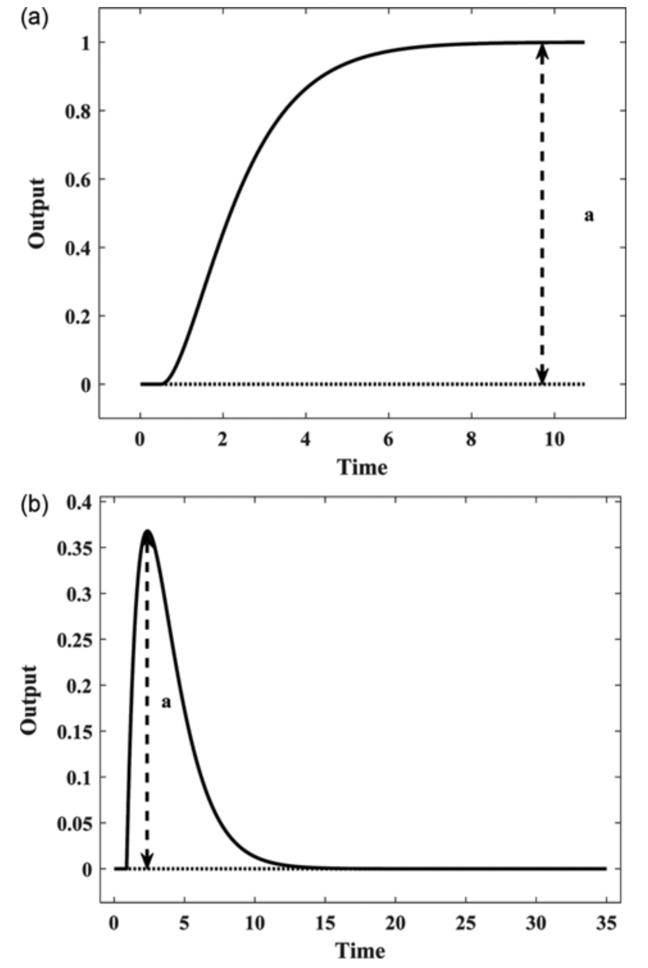

Fig. 3. Step response for the open-loop case (Fig. 1(a)) (a) and the closed-loop case (Fig. 1(b)) (b).

closed-loop type batch control case (Fig. 1(b)).

To make the proposed controller eliminate the process error faster and more stable, gain scheduling can be used [12]. Although a tight gain can reduce process error quickly, it decreases the robustness of the control system. To overcome this, for example, the batch PID control gain can be reduced to the half of the initial gain when the mean squares error becomes a quarter of that of the initial batch.

The tuning parameters for the weight function are decided as below. Eq. (7) shows the overall transfer function of the closed-loop batch control case.

$$G_{OL}(s)=\frac{G(s)}{1+G_{c,\,feedback}(s)G(s)} \tag{7}$$

where, G(s) is the transfer function of the process and $G_{c,feedback}$ is the transfer function of the feedback controller of Eq. (8):

$$G_{c,\,feedback}(s)=k_{c,\,feedback}\left(1+\frac{1}{\tau_{i,\,feedback}s}+\tau_{d,\,feedback}s\right) \tag{8}$$

The high order transfer function of Eq. (7) can be approximated to the FOPTD model of Eq. (9) by reducing Eq. (7) to the FOPTD model using the model reduction method [12].

$$G_{OL}(s)=\frac{k_{OL}\exp(-\theta_{OL}s)}{1+\tau_{OL}s} \tag{9}$$

In the case of the open-loop batch control case, the overall transfer function (G_{OL}) corresponds to the process. So, (9) is obtained by reducing the process model to the FOPTD model using the model reduction method [12]. In this research, $\tau_w=\tau_{OL}$ and $\theta_w=\theta_{OL}$ are recommended to determine the tuning parameters of the weight function, respectively.

SIMULATION

Several case studies were performed to demonstrate the control performance of the proposed method. Process 1 in Table 1 is used to represent how to implement the proposed batch control method. Here, the batch PID controller with the feedback controller (Fig. 1 (b)) is used. First, the target process is reduced to the FOPTD model (k_{re}=1.0, t_{re}=2.38, and θ_{re}=0.93), and the feedback controller is tuned using ITAE-1 ($k_{c,fb}$=2.15, $\tau_{i,fb}$=3.23 and $\tau_{d,fb}$=0.31) [12]. After that, a=0.386 is obtained from the step input disturbance response of this closed loop system to tune the batch PID controller. Then, the tuning parameters of $k_{c,\,batch}$=0.816, $\tau_{i,\,batch}$=0.25, and $\tau_{d,\,batch}$=1.0 for the batch PID controller are derived by the proposed tuning rules. Fig. 4(a) confirms that the proposed batch controller provides better control performance as the batch number increases, and it takes over the control action of the feedback PID controller as illustrated in Fig. 4(c). In Fig. 4(b), the mean square error of all the control errors of each batch is chosen as the numerical measure to define the batch-wise performance. It dramatically decreases as the batch number increases, proving batch-wise improvement. The proposed batch controller also shows acceptable control performance in case

Table 1. Information on simulation studies

		Reduced FOPTD model			Feedback control parameters			Batch control parameters		
Process	Transfer function	k_{re}	τ_{re}	θ_{re}	$k_{c,fb}$	$\tau_{i,fb}$	$\tau_{d,fb}$	$k_{c,\,batch}$	$\tau_{i,\,batch}$	$\tau_{d,\,batch}$
Process 1: usual process	$G(s)=\frac{\exp(-0.5s)}{(s+1)^2}$	1.0	2.38	0.93	2.15	3.23	0.31	1.09	1.0	0.25
Process 2: high order	$G(s)=\frac{\exp(-0.1s)}{(s+1)^3}$	1.0	3.98	1.12	2.83	5.7	0.38	1.09	1.0	0.25
Process 3: inverse response	$G(s)=\frac{(1-0.1s)\exp(-0.5s)}{(s+1)^2}$	1.0	2.21	1.05	1.82	3.04	0.34	1.09	1.0	0.25

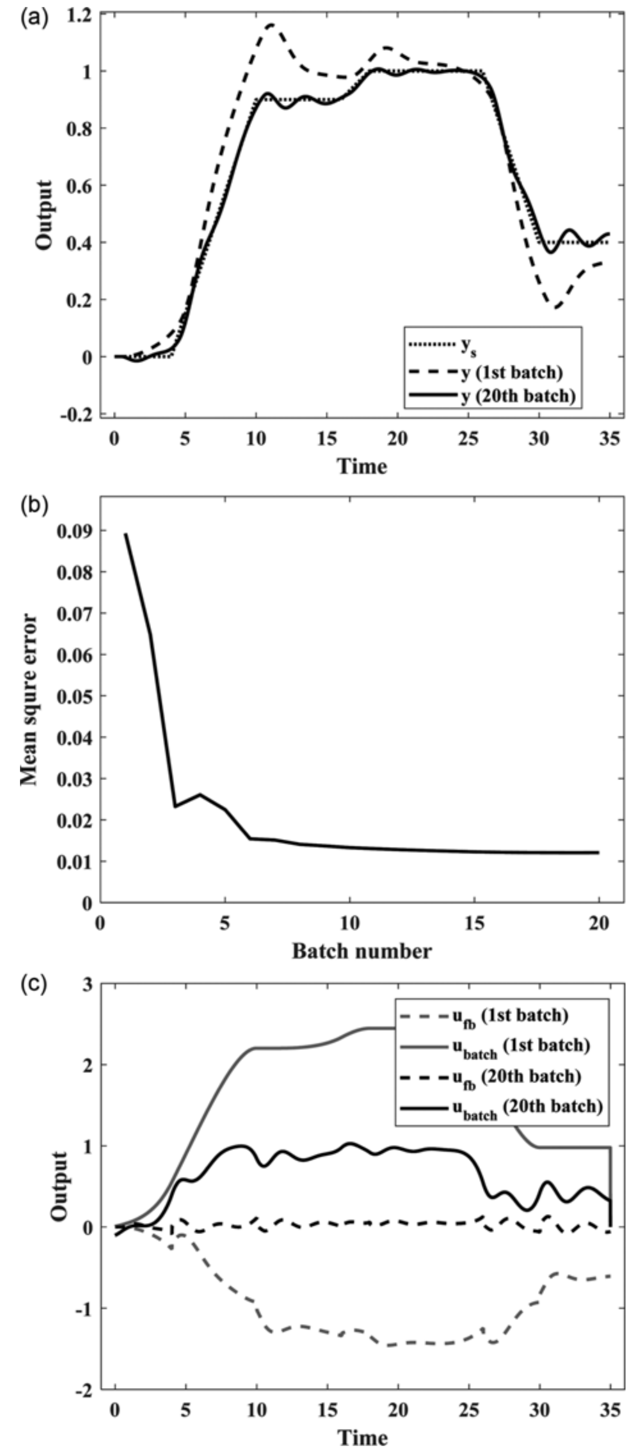

Fig. 4. Control performance of the proposed batch PID controller with feedback controller for process 1: (a) Process output, (b) control error with respect to batch number, (c) control outputs.

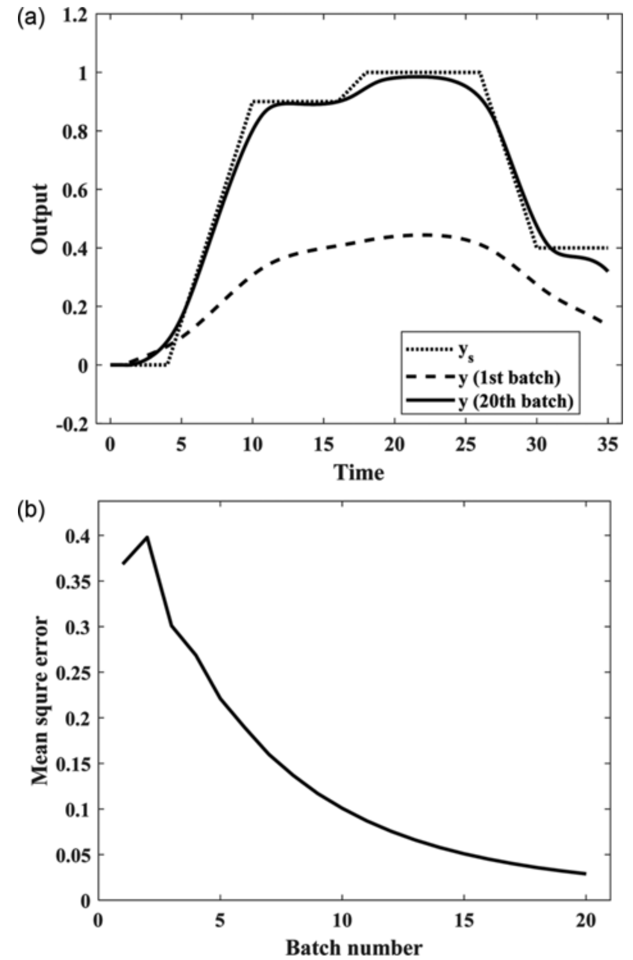

Fig. 5. Control performance of the proposed batch PID controller without feedback controller for process 1: (a) Process output, (b) control error with respect to batch number.

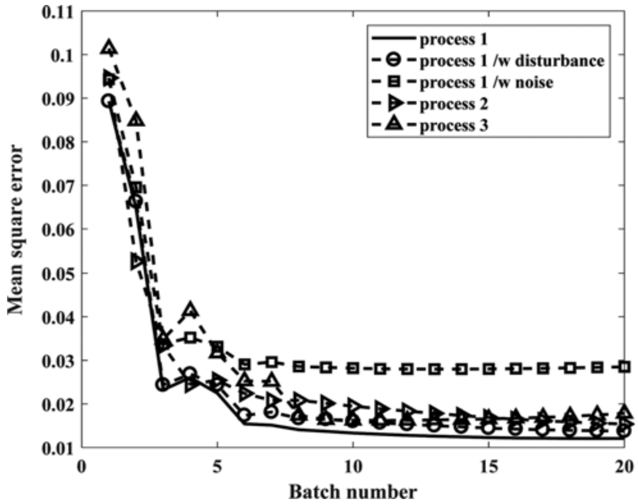

Fig. 6. The performance of the proposed controller in terms of batch number.

of the open loop control structure (Fig. 1(a)), as demonstrated in Fig. 5.

The proposed batch controller also provides good control performance for various processes enumerated in Table 1. As shown in Fig. 6, it eliminates the controller error efficiently as increasing the batch number, even in the processes with unknown disturbance ($d(t)=0.05\sin(2\pi t)+0.1\sin(1.2\pi t)+0.05\sin(0.6\pi t)$) and measurement noise (uniformly distributed random noise between –0.05

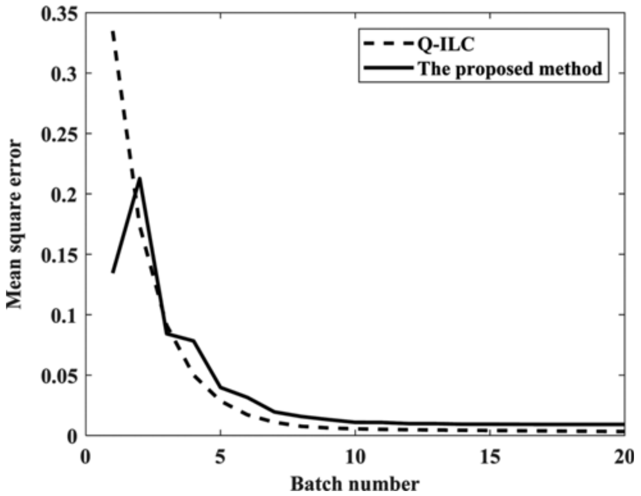

Fig. 7. The performance comparison between the proposed method and Q-ILC method.

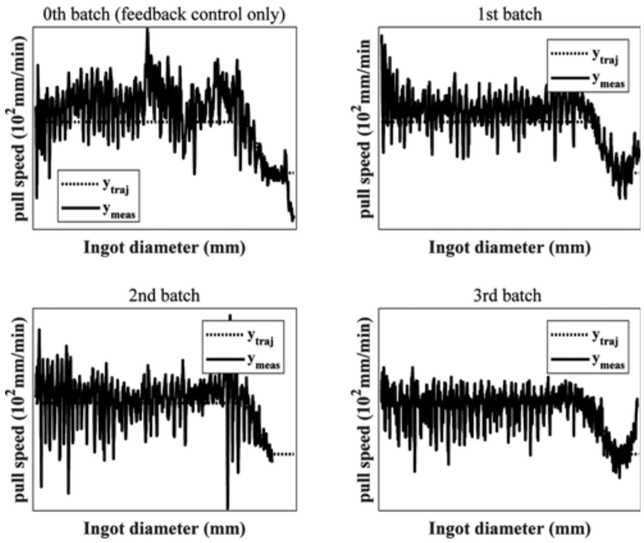

Fig. 9. The batch control data of the single crystal grower process with the proposed controller.

and 0.05).

Fig. 7 compares the proposed method ($k_{c, batch}$=0.27, $\tau_{i, batch}$=0.29 and $\tau_{d, batch}$=0.05) with one of the previous methods, Q-ILC (quadratic criterion iterative learning control) [14]. Since Q-ILC is model-based optimal control, it guarantees the best control performance. So, it is natural that Q-ILC is better than the proposed method from the control performance point of view. However, Q-ILC requires a relatively accurate process model and heavy computational load to implement it in real industry, while the proposed method is model-free and very simple like the conventional PID control. Also, the control performance of the proposed method is close to that of Q-ILC as shown Fig. 7. Putting it all together, we believe that the proposed method can significantly contribute to improving the control performance of the batch process from the practical point of view.

APPLICATION TO REAL PROCESSES

The proposed method is applied to real processes of Czochralski single crystal growing batch reactors. The diameter of the ingot and the pull speed should be strictly controlled to obtain a high quality of the single crystal ingot. Fig. 8 shows the control structure for the grower. It is composed of three the feedback controllers of the automatic diameter controller (ADC), automatic growth controller (AGC) and automatic temperature controller (ATC) and the proposed batch PID controller. Diameter Target, PS Target and ATC Recipe in Fig. 8 denote the diameter setpoint, pull speed setpoint and control output of the proposed batch PID controller, respectively. Fig. 9 represents the pull speed control performance when the proposed batch control is applied to the single crystal grower, confirming that it successfully removes the control errors more and more as the batch number increases. The detailed parameters of the controllers and the units of the process variables cannot be opened because they are confidential information. The proposed batch control for the Czochralski single crystal grower has

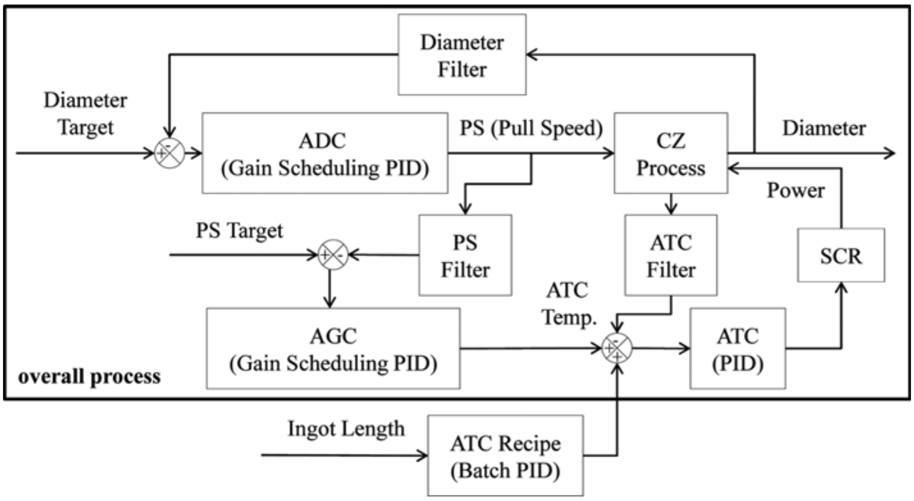

Fig. 8. The control structure for the single crystal grower process.

been used for over two years in major ingot production companies and has significantly contributed to the production of high quality ingots and reduction of off-specs. It is recognized that the proposed batch PID control method can be applied to industry without any serious problems through successful applications to real plants.

CONCLUSIONS

A new batch proportional-integral-derivative (PID) controller is proposed to improve the control performances of batch processes. It guarantees many advantages of simplicity, good performance, robustness, with no accurate model required by extending the concept of the conventional feedback PID controller for continuous processes to the case of batch processes. Two, the structures of the open-loop type batch control case and the closed-loop type batch control case are used to implement the proposed batch PID controller. It can remove the control errors more and more as the batch operation proceeds since the bath PID control action is batch-wise rather than time-wise.

The simulation results demonstrate that the proposed batch PID controller provides good control performance in the setpoint tracking and rejecting various disturbances and good robustness to uncertainties such as noises and variation of the process dynamics. Moreover, applications to real batch processes of a single crystal grower confirm that it can significantly contribute to increasing production rate and decreasing off-specs by solving control problems in industry.

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