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Performance assessment for iterative learning control of batch units

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ABSTRACT

A new method is developed to estimate the minimum variance bounds and the achievable variance bounds for the assessment of the batch control system when the iterative learning control is applied. Unlike continuous processes, the performance assessment of batch processes requires particular attention to both disturbance changes and setpoint changes. Because of the intrinsically dynamic operations and the non-linear behavior of batch processes, the conventional approach of controller assessment cannot be directly applied. In this paper, a linear time-variant system for batch processes is used to derive the performance bounds from the routine operating batch data. The bounds at each time point computed from the deterministic setpoint and the stochastic disturbance for the controlled output variance can help create simple monitoring charts. They are used to track the progress easily in each batch run, to monitor the occurrence of the observable upsets, and to accordingly improve the current performance. The applications are discussed through simulation cases to demonstrate the advantages of the proposed strategies.

1. Introduction

In the past two decades, the chemical industry has undergone significant changes as the energy cost is rising and the global competition in price and quality is increasing. In agile manufacturing, product objective changes dynamically with customers' demands. The manufacturing trend is shifted from conventional continuous manufacturing plants toward flexible batch plants with multiple products [1]. This is especially true for manufacturing of high value-added products, such as bioproducts, pharmaceuticals, polymers, specialty chemicals, and semiconductor materials. The control design in batch processes is quite different from that in continuous ones. When the process is operated continuously, there is a variety of methodologies in the feedback control loop system to ensure closed-loop stability and to achieve acceptable steady-state performance with respect to setpoint and disturbance inputs. Because of the intrinsically dynamic operations of batch processes, the conventional approach of the controller assessment cannot be directly applied. The conventional controller design for the continuous process may not be able to achieve a specified profile response and to process raw materials into products in finite duration.

The operational challenges of dynamic batch control have been discussed [2,3]. Interest in research and development of batch control based on iterative learning control has increased steadily since the term, iterative learning control (ILC), was first presented [4]. ILC of batch operation allows the extraction of information from the past batches to refine the new batch run and to improve the performance of tracking control for product quality. ILC utilizes a feedback controller for stabilizing the closed-loop system. It also uses a feedforward controller for designing the transient response of the operating profile. Numerous ILC schemes have been developed in the past decades. They enhanced the control performance over a fixed time interval iteratively [5–7]. The effect of ILC on a continuous controlled system to improve the performance has been proven [8,9]. Comprehensive review of this topic is shown in Refs. [5,10]. The webpage for iterative learning control research is linked (http://www.ece.usu.edu/csois/ilc/ILC/index.html). Lee et al. integrated iterative learning control into conventional model predictive control and applied it to batch processes [11]. Because of the large variation of batch processes in the operation condition during a batch run, model predictive control with artificial neural networks came into place for on-line optimization [12]. Huzmezan et al. applied an adaptive control to a PVC reactor and an ethoxylated fatty acid reactor [13]. However, these control research papers focused mainly on design strategies. They did not show how good the current controller performance of the batch operation was in comparison with benchmark control. In control engineering practice, the control method is designed based on a nominal model. However, plant models are often subject to certain kind of uncertainty. The robust issues in ILC, like parametric uncertainties, iteration-domain frequency uncertainty, and iteration-domain stochastic uncertainty, have been discussed [14–17]. The aim of the controller performance assessment is to determine and measure the capability of control systems in order to improve

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the degradation performance. If the deterioration of controller performance cannot be identified in time, the malfunction would cause inconsistent product quality and monetary loss or even a significant impact on personnel, environmental and equipment safety.

The performance assessment of the control loop based on the minimum variance was first presented by Harris [18]. Several techniques using the minimum variance have been proven useful in prioritizing the activities of process engineers, including monitoring and assessing the controller performance [19,20]. In the research, the controller performance is evaluated based on the output variance of the stochastic performance coming from the unmeasured disturbance driven by white noise. However, the controller performance of the batch operation is influenced not only by the unmeasured disturbance but also by the deterministic regulation which is defined by the setpoint changes. Qin mentioned that the performance assessment techniques could be categorized into stochastic performance monitoring and deterministic performance monitoring [21]. Since the deterministic regulation is very different from the stochastic one, their achievable performance bounds should be separated [22]. Although there were many research papers on assessing continuous control systems, to our best knowledge, the assessment of the batch control system was never mentioned.

In this paper, two issues are addressed to assess the controller performance of the batch operation. First, the minimum variance performance bound is developed for batch operation systems. The performance bound can subsequently be used for the performance assessment of the batch system control loop. It is considered a benchmark of performance. Interestingly, the performance bound at each operating time point can be achieved by the traditional minimum variance control law. However, because of the controller structure, researchers in the past believed that the designed controller could not meet the theoretical variance benchmark when processes contained non-stationary disturbance [21,23]. Secondly, an achievable minimum variance performance bound is estimated for the controllers used in the batch system. The multiple objective optimization technique is adopted. It allows tracking the setpoint and rejecting the disturbance simultaneously. Once the performance bounds at each time point are set up, like traditional performance assessment approaches in the continuous system, they can create simple monitoring charts to track the progress in each batch run, to monitor the occurrence of the observable upsets, and to accordingly improve the current performance.

The remaining paper is structured as follows: The problem of the performance assessment in the batch operation system is defined in Section 2. Without specifying the control task, it is difficult to assess the performance of the control loop. In Section 3, the performance assessment bounds of the batch control system are derived. With only the past operating data, the achievable performance and the corresponding optimal parameters based on the closed identification schemes are developed in Section 4. The effectiveness of the proposed method and its potential applications are demonstrated through two computer simulation problems, including a simple linear system and a non-linear batch reactor in Section 5. Finally, concluding remarks are made.

2. Configuration of ILC of batch units

Most of the performance assessments of the continuous processes were developed based on linear time-invariant (LTI) model. There were only a few methods for time-variant processes [24,25]. In practice, most batch processes have a certain degree of the intrinsic non-linear and time varying characteristics, such as polymerization reactors and biochemical reactors. This will make the linear assumption of the control performance assessment more difficult. In spite of the drawbacks, it is easy to extend the performance assessment techniques from LTI processes to linear time-variant (LTV) processes [26]. The advantage of the performance assessment of LTV is easy analysis of a transfer function system for the contribution of the desired setpoint and the unmeasured disturbance to the process output. Hence, in this paper, the LTV model for the batch process is used to assess the performance of the batch process with non-linearity or large operation regime.

Suppose there is an operation of a batch run (i). The feedback control structure for the batch system is shown in Fig. 1. A discrete linear time-variant process of the following form which is any linear time-invariant process governed by the transfer function models is given

$$y(i,k) = G_p(q^{-1},k)u(i,k) + G_w(q^{-1},k)w(k) \tag{1}$$

where the controlled output $y(i,k)$ at time point (k) can be expressed as the sum of two terms, one for the deterministic manipulated input ($u(i,k)$) and the other for the white noise disturbance ($w(k)$). The process ($G_P(q^{-1}, k)$) and the disturbance ($G_w(q^{-1},k)$) transfer functions vary with time. In Fig. 1, the dashed block represents lumping of all the elements in the feedback process. The aims of the batch control system are not only at achieving disturbance rejection but also at tracking the desired reference. However, one single feedback controller ($G_c(q^{-1},k)$) can not fit the above requirements satisfactorily. In many cases, the control performance of the setpoint tracking is not acceptable even if the disturbance rejection is satisfactory. To complement this, the iterative improvement strategy with a two-degree of freedom structure is widely applied to progressively tracking error by improving its control action estimates. In Fig. 2, a block diagram interpretation of the ILC scheme is shown. The dashed block in Fig. 1 denotes the feedback process for the time-varying closed loop system at a particular run in Fig. 2. The principle of ILC makes use of the measurement ($y(i,k)$) and the reference signal ($x^{sp}(i,k)$) of the previous batch run for control during the current batch ($i+1$) under the disturbance input ($w(k)$). The feedback controller ($G_c(q^{-1},k)$) undertakes correction based on non-deterministic disturbances and the deterministic reference signal. The feedforward controller ($G_f(q^{-1},k)$) adjusts the reference based on the output errors. The control design describes how a change in the control input affects the system response from one repetition to the next. The control structure can be regarded as a two-dimensional model that is the function of the operation number in the trial domain and the operation time in the time domain. The learning control objectives are to determine the controllers, $G_c(q^{-1},k)$ and $G_f(q^{-1},k)$, to generate an appropriate control input time history and to produce a detailed output history through iterative trails. In minimum variance control, the minimum variance bound of the ILC system for all batch runs is defined as

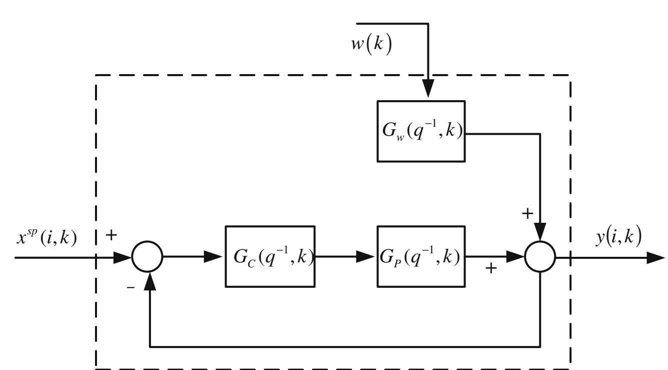

Fig. 1. Block diagram of feedback control for the batch system.