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An integrated iterative learning control strategy with model identification and dynamic R-parameter for batch processes

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ABSTRACT

An integrated iterative learning control strategy with model identification and dynamic R-parameter is proposed in this paper. It systematically integrates discrete-time (batch-axis) information and continuous-time (time-axis) information into one uniform frame, namely the iterative learning controller in the domain of batch-axis, while a PID controller (PIDC) in the domain of time-axis. As a result, the operation policy of batch process can be regulated during one batch, which leads to superior tracking performance and better robustness against disturbance and uncertainty. Moreover, the technologies of model identification and dynamic R-parameter are employed to make zero-error tracking possible. Next, the convergence and tracking performance of the proposed learning control system are firstly given rigorous description and proof. Lastly, the effectiveness of the proposed method is verified by examples.

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1. Introduction

Batch processes have been used increasingly in the production of low volume and high value added products, such as special polymers, special chemicals, pharmaceuticals, and heat treatment processes for metallic or ceramic products [1]. For the purpose of deriving the maximum benefit from batch processes, it is essential to optimize the operation policy of batch processes. Therefore, optimal control is crucial to the efficient operation of batch processes. However, with strong nonlinearity and dynamic characteristics, optimal control of batch processes is more challenging than that of continuous processes and thus it needs new non-traditional techniques. Therefore, the optimal control of batch processes remains a challenging in modern industrial control.

Batch processes have the characteristic of repetition, and thus iterative learning control (ILC) can be used in the optimization control of batch processes [2–4]. After its initial development for industrial robot [5], ILC has been increasingly practiced for batch processes with repetitive natures to realize perfect tracking and control optimization [6,7]. Xiong and Zhang presented a batch-to-batch iterative optimal control method based on recurrent neural network models to solve the model prediction errors problem [8]. Lee et al. proposed the optimal iterative learning algorithm based on linear time-varying models for the temperature control of batch processes [9,10]. However, in most reported results, only the batch-to-batch performance is taken for consideration but not the performance of real-time feedback. Thus, ILC is actually an open-loop control from the view of a separate batch because the feedback-like control just plays role between different batches. As a result, it is difficult to guarantee the performance of the batch process when uncertainties and disturbances exist. Therefore, an integrated optimization control system is required to derive the maximum benefit from batch processes, in which the performance of time-axis and batch-axis are both analyzed synchronously. Rogers firstly employed two-dimension (2D) theory to solve above-mentioned problem [11]. Li et al. presented an ILC strategy for 2D time-invariant linear repetitive systems with fixed time delays [12]. Chin et al. proposed a two-stage iterative learning control technique by using the real-time feedback information to modify the ILC parameters for independent disturbance rejection [13]. Gao's research group did a series of 2D optimization control-based research for batch processes [14,15]. However, most reported results assume that the prediction errors of the model were zeros after the first cycle without considering model uncertainties and exogenous disturbance [16]. Liu et al. combined the internal model control (IMC) with the ILC to deal with uncertain time delay for linear batch processes [17]. To guarantee robust convergence along both time and batch directions, a 2D ILC scheme which integrates feedback control with feedforward control was developed for robust tracking of desired trajectory [18]. Recently,

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Nomenclature

k	batch index
t_f	batch run length
y_d	specified reference trajectory
$u_k^{\mathrm{ILC}}(t)$	input variable under ILC method
$u_k^{\mathrm{PIDC}}(t)$	input variable under PIDC method
$u_k(t)$	integrated input variable
$y_k(t)$	output variable
$\hat{y}_k(t)$	predicted output of data-based model
$y(\mathbf{U}_k^{\mathrm{ILC}}, t_f)$	output variable of end-point product qualities under ILC method
$\hat{y}(\mathbf{U}_k^{\mathrm{ILC}}, t_f)$	predicted output variable of data-based model under ILC method
$e(\mathbf{U}_k, t_f)$	tracking error of end-point product qualities under integrated method
$e(\mathbf{U}_k^{\mathrm{ILC}}, t_f)$	tracking error of end-point product qualities under ILC method
$\hat{e}(\mathbf{U}_k^{\mathrm{ILC}}, t_f)$	tracking error of data-based model under ILC method
$\mathbf{U}_k$	integrated input at the kth batch run
$\mathbf{U}_k^{\mathrm{ILC}}$	control sequence obtained from ILC controller at the kth batch run
$\mathbf{U}_k^{\mathrm{PIDC}}$	control sequence computed from PID controller at the kth batch run
$\mathbf{Y}_k$	measured product quality sequence at the kth batch run
$\hat{\mathbf{Y}}_k$	predicted product quality sequence at the kth batch run
$\mathbf{Q}$	weighting matrix for tracking error in ILC
$\mathbf{R}_{k+1}$	weighting matrix for control change in ILC
ε	small positive constant

Wang et al. proposed an advanced ILC-based PI control for MIMO batch processes to hold robust stability based on a 2D system formulation [19]. For piecewise affine batch processes, Liu et al. proposed a 2D closed-loop ILC method for robust tracking of the set-point profile against uncertainties and disturbances [20].

Motivated by previous works, an integrated iterative learning control system combining discrete-time (batch-axis) information with continuous-time (time-axis) information is proposed in our recent work [21]. Similar to most new controller design methods developed in the literature, perfect model assumption is assumed in that work in order to develop the first of its kind that guarantees the convergence of control policy with the proposed integrated control scheme derived from a rigorous proof. But in practical application, model-plant mismatch is inevitable. Thus with the consideration of mode-plant mismatch and uncertainty, an integrated iterative learning control strategy with model identification and dynamic R-parameter is proposed in this paper. It systematically integrates discrete-time (batch-axis) information and continuous-time (time-axis) information into one uniform frame, namely the iterative learning controller in the domain of batch-axis, while an PID controller (PIDC) in the domain of time-axis. As a result, the batch process can be regulated during one batch, which leads to superior tracking performance and better robustness against disturbance and uncertainty. Moreover, the technologies of model identification and dynamic R-parameter are employed to make zero-error tracking possible. Next the convergence and tracking performance of the proposed iterative learning control system are firstly given rigorous description and proof.

The paper is structured as follows. Section 2 gives a brief description of batch processes discussed in this paper. Section 3 presents the proposed integrated learning control system. Performance analysis is presented in Section 4 and the simulation example is given in Section 5, followed by the concluding remarks given in Section 6.

2. The description of batch processes

A batch process is referred to a process repetitively performing a specified task over a certain period of time named as cycle. In this paper, the discussed batch process can be described by the following state-space representation

$$\begin{cases} \dot{\mathbf{x}}_k(t) &= \mathbf{A}\mathbf{x}_k(t) + \mathbf{B}u_k(t) \\ &= [\mathbf{A}_0 + \Delta\mathbf{A}]\mathbf{x}_k(t) + [\mathbf{B}_0 + \Delta\mathbf{B}]u_k(t) \\ y_k(t) &= \mathbf{C}\mathbf{x}_k(t) \\ \mathbf{x}_k(0) &= \mathbf{x}_0, \quad k = 1, 2, \ldots \end{cases} \tag{1}$$

where t and k denote time and cycle indices, respectively. $\mathbf{x}_k(t)$, $u_k(t)$ and $y_k(t)$ are, respectively, the state, the control input and the batch process output at time t in kth cycle, and x_0 is the initial state of each cycle. $\mathbf{A}_0$, $\mathbf{B}_0$, $\mathbf{C}$ are known real constant matrices with appropriate dimensions, $\Delta\mathbf{A}$ and $\Delta\mathbf{B}$ denote time-varying uncertainties in the system model, and are assumed to be bounded naturally.

3. Integrated iterative learning control strategy with model identification and dynamic R-parameter for batch processes

The formulation of the proposed integrated iterative learning control strategy with model identification and dynamic R-parameter is depicted in Fig. 1, where k, $u_k(t)$ and $y_k(t)$ are same as those defined in Section 2, $y_d(t)$ is desired product quality, $u_k^{\mathrm{ILC}}(t)$ and $u_k^{\mathrm{PIDC}}(t)$ are ILC control action variable and PIDC control action variable, and $u_k(t) = u_k^{\mathrm{ILC}}(t) + u_k^{\mathrm{PIDC}}(t)$. $e_k(t)$ represents the error between the measured output and the desired product quality. Batch length is defined as t_f. Here the batch length t_f is divided into L equal intervals. $G(s)$ denotes the batch process, and $C(s)$ represents the PID controller.

Define that $\mathbf{U}_k$ is the integrated input sequence of kth batch, which consists of the control policy of $\mathbf{U}_k^{\mathrm{ILC}}$ obtained from ILC optimization controller and the control policy of $\mathbf{U}_k^{\mathrm{PIDC}}$ computed from PIDC controller. $\mathbf{Y}_k$ and $\hat{\mathbf{Y}}_k$ are the corresponding product quality sequence and predicted product quality sequence. In the proposed integrated iterative learning control system, $\mathbf{U}_k$, $\mathbf{Y}_k$ and $\hat{\mathbf{Y}}_k$ are stored to eliminate the model-plant mismatch. Based on the information from previous batch, the optimization controller can find an updating mechanism for the input sequence $\mathbf{U}_k^{\mathrm{ILC}}$ of the new batch using improved iterative optimal control law derived by the rigorous mathematic proof method discussed shortly. At next batch, this procedure is repeated to let the product qualities asymptotically converge toward $y_d(t_f)$ at the batch end.

3.1. Integrated iterative learning control system with dynamic R-parameter

As discussed above, the proposed integrated learning optimization control action can be described as

$$\mathbf{U}_k = \mathbf{U}_k^{\mathrm{ILC}} + \mathbf{U}_k^{\mathrm{PIDC}} \tag{2}$$

Owing to the model-plant mismatch, the process output may not be same as the one predicted by the model. The offset between the measured output and the model prediction is termed as model prediction error defined by

$$\hat{e}_k(t) = y_k(t) - \hat{y}_k(t) \tag{3}$$

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