Journal of Process Control 20 (2010) 173–180

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

IMC-based iterative learning control for batch processes with uncertain time delay

Tao Liu [a], Furong Gao [a,*], Youqing Wang [b]

[a] Department of Chemical and Biomolecular Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
[b] Department of Chemical Engineering, University of California Santa Barbara, CA, USA

ARTICLE INFO

Article history:
Received 18 May 2009
Received in revised form 30 July 2009
Accepted 20 October 2009

Keywords:
Batch process
Uncertain time delay
Internal model control (IMC)
Iterative learning control (ILC)
Convergence

ABSTRACT

Based on the internal model control (IMC) structure, an iterative learning control (ILC) scheme is proposed for batch processes with model uncertainties including time delay mismatch. An important merit is that the IMC design for the initial run of the proposed control scheme is independent of the subsequent ILC for realization of perfect tracking. Sufficient conditions to guarantee the convergence of ILC are derived. To facilitate the controller design, a unified controller form is proposed for implementation of both IMC and ILC in the proposed control scheme. Robust tuning constraints of the unified controller are derived in terms of the process uncertainties described in a multiplicative form. To deal with process uncertainties, the unified controller can be monotonically tuned to meet the compromise between tracking performance and control system robust stability. Illustrative examples from the recent literature are performed to demonstrate the effectiveness and merits of the proposed control scheme.

1. Introduction

Significant progress has been made for both technologies and applications of iterative learning control (ILC) in the past decade for batch processes, e.g., chemical distillation/crystallization reactors, industrial injection molding machines, and robotic manipulators [1], owing to that this type of control technique can progressively improve system performance for setpoint tracking and load disturbance rejection using historical cycle data [2]. As surveyed in the recent papers [1,3], quite an amount of ILC control methods have been well developed in both continuous- and discrete-time domains that can realize perfect tracking for linear or nonlinear batch processes. Presently, the challenges for practical applications of ILC are mainly associated with robust convergence and stability against process uncertainties.

Recently, a number of references have presented robust ILC methods to cope with structured and unstructured process uncertainties for delay-free or known time delay batch processes. In frequency domain, a robust ILC design method [4] was proposed for delay-free linear time-invariant (LTI) batch processes based on the linear fractional transformation (LFT) analysis of robust control theory [5]; Gorinevsky [6] extended the loop shaping method [7] for ILC design with phase/magnitude margin; using the Smith predictor control structure, which is well known for superior control of time delay processes with a priori knowledge of the time delay, several ILC algorithms [8,9] were proposed to improve tracking performance of ILC for batch processes with obvious time delay; Tan et al. [10] developed an ILC tuning of proportional-integral-derivative (PID) controller in the framework of the conventional unity feedback structure to enhance load disturbance rejection; an ILC strategy for tuning a dual-mode controller was recently proposed for optimal heating of exothermic batch reactors [11]; to deal with output delay of a non-minimum phase plant, a reference shift algorithm was suggested based on a double-loop ILC structure [12]. In time domain, Park et al. [13] proposed an ILC method in terms of a holding mechanism for the control input during the estimated time delay for operation of batch processes with time delay; from a two-dimensional (2D) view (i.e., time-wise and batch-wise) for batch process control design [14], a state-space ILC method was presented in terms of using a 2D linear continuous-discrete Roesser's model [15]. Equivalent convergence conditions for ILC design in either frequency or time domain were analyzed in the recent papers [16–18].

Meanwhile, in discrete-time domain, robust ILC methods for batch processes with model uncertainties or unmodeled dynamics have also been proposed by comparison. Using historical data to modify output prediction from cycle to cycle, on-line adaptive ILC methods [19,20] were presented to deal with model mismatch. Based on a 2D system description, a series of ILC methods [21–24] have been developed using a linear quadratic optimal control criterion and robust stability conditions of linear matrix inequalities to deal with a variety of model uncertainties. To accommodate for implemental constraints, model predictive control (MPC) based ILC schemes were proposed in the recent papers [25–29]. Using the real-time feedback information to modify the ILC parameters, Chin et al. [30] presented an improved strategy for independent

* Corresponding author. Tel.: +852 2358 7139; fax: +852 2358 0054.
E-mail address: kefgao@ust.hk (F. Gao).

0959-1524/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jprocont.2009.10.008

disturbance rejection. With an inherent lag compensation in the updating law, Tan et al. [31] proposed an ILC algorithm for batch processes with input delay or phase lag. Based on estimating the minimum variance bound and the achievable variance bounds from batch to batch, Chen and Kong [32] developed an ILC method for progressively improving operation of time delay batch processes.

In view of that time delay mismatch is commonly associated with other process uncertainties during operation of a time delay batch process in engineering practice, this paper proposes a robust ILC method based on the internal model control (IMC) structure [33] to deal with such difficulties. Sufficient conditions to guarantee the convergence of ILC are derived for time delay batch processes with or without model uncertainties. To facilitate the controller design, a unified controller structure in terms of the standard IMC controller form is proposed for implementation of IMC in the initial run and the subsequent ILC in the proposed control scheme. An important merit is that both IMC and ILC can be independently designed to deal with the process uncertainties. Moreover, the unified controller can be monotonically tuned to meet the compromise between tracking performance and control system robust stability. For practical applications with measurement noise, denoising strategies are given to enhance convergence robustness. The paper is organized as follows: Section 2 introduces the proposed IMC-based ILC scheme and the general transfer function form of time delay batch processes studied in this paper. In Section 3, an IMC design for the initial run of the proposed control scheme is given in terms of the general transfer function, together with a robust tuning constraint for maintaining the control system stability against process uncertainties. In Section 4, sufficient conditions to guarantee the convergence of ILC in the proposed control scheme are derived, and correspondingly, a unified controller form is proposed for the convenience of implementing both IMC and ILC in the proposed control scheme. Denoising strategies are presented in Section 5 to enhance convergence robustness against measurement noise associated with practical applications. Illustrative examples are given in Section 6 to demonstrate the effectiveness and merits of the proposed control scheme. Finally, conclusions are drawn in Section 7.

2. IMC-based ILC scheme

It is well known that perfect tracking can be obtained by the standard IMC structure [33] only for the case where there is no uncertainty associated with the process and load disturbance. Given a constant or step-like setpoint commonly practiced, IMC structure may be used to ensure no steady-state offset for a batch process, if the cycle time (T_{P}) is long enough. Moreover, IMC structure may be used to cope with process uncertainties, that is to say, maintaining the closed-loop system robust stability. These nice features of IMC inspire the development of an IMC-based ILC control scheme in this paper, in light of that given any bounded signals injected into an IMC system with process uncertainties, including any feedforward control signal of ILC that may be independently designed for perfect tracking, only bounded output can be yielded if the IMC system maintains robust stability.

The proposed control scheme is shown in Fig. 1, where the transfer function block diagram encircled by a dashed line is the ILC part, and the rest part is the standard IMC structure; R (i.e., r in time domain expression) denotes the setpoint, Y (i.e., y in time domain expression) the process output, and D load disturbance; C is the IMC controller and also used for implementation of ILC, $G_{\mathrm{m}} = G_{\mathrm{mo}}e^{-\theta s}$ the process model, G_{d} the load disturbance transfer function; 'Memory' is a storage used for recording the current cycle information of process output (Y_k), predicted output ($\widehat{Y}_k = G_{\mathrm{m}}U_k$) and the control input to the process (U_k), and providing the last cycle information of process output (y_{k-1}), predicted output ($\hat{y}_{k-1}$) and control input (U_{k-1}); V_k is the ILC updating information used to compute the control increment (U_{C}) for adjustment of U_k.

For implementation, the initial run ($k = 1$) of the proposed control scheme is exactly an IMC strategy with zero initialization of the ILC control law (i.e., $V_1 = U_0 = 0$). Starting from the second run ($k \geqslant 2$), the whole control structure is implemented as an ILC scheme, based on the IMC control law (U_1) stored in the 'Memory'. The key idea behind such implementation is that, based on an IMC control law prescribed to accommodate for the process uncertainties with stability margin, the ILC control law, which is essentially of feedforward control, is subsequently added to progressively realize perfect tracking, according to the linear superposition principle. Hence, relative independence can be obtained for designing the IMC control law to maintain the control system robust stability and the ILC control law to realize perfect tracking, respectively.

A time delay process denoted as G in Fig. 1 is generally modeled in the transfer function form of

$$G_{\mathrm{m}}(s) = G_{\mathrm{mo}}e^{-\theta_{\mathrm{m}}s}, \tag{1}$$

where G_{mo} is a rational proper transfer function, and θ_{m} the process response delay. Since ILC design is herein studied for operation of inherently stable batch processes, we may further express G_{mo} as

$$G_{\mathrm{mo}}(s) = k_{\mathrm{p}}\frac{B_{+}(s)B_{-}(s)}{A(s)} \tag{2}$$

where k_{p} denotes the process gain, $A(0) = B_{+}(0) = B_{-}(0) = 1$, all zeros of $A(s)$ and $B_{-}(s)$ are located in the complex left-half-plane (LHP), and all zeros of $B_{+}(s)$ are located in the complex right-half-plane (RHP). Denote that $\deg\{A(s)\} = m$, $\deg\{B_{-}(s)\} = n_1$, and $\deg\{B_{+}(s)\} = n_2$. Generally, it is true that $n_1 + n_2 < m$ in practice, which indicates that G_{mo} is strictly proper.

Denote Y_{d} (i.e., y_{d} in time domain expression) as the desired output trajectory. Through out this paper, we assume that the initial resetting condition is satisfied, i.e., $r(0) = y_{\mathrm{d}}(0) = y_k(0)$, where k denotes the cycle number, and without loss of generality, we consider that $y_{\mathrm{d}}(0) = y_k(0) = 0$ for the convenience of analysis. In the following sections respectively for IMC and ILC designs, the Laplace variable, s, will be omitted when this does not lead to any confusion.

3. IMC design

With a process model obtained in the form of (1) and (2), to achieve the H_2 optimal setpoint tracking performance, it follows from the IMC theory [33] that the controller should be designed as

$$C_{\mathrm{IMC}}(s) = \frac{A(s)}{k_{\mathrm{p}}B_{-}(s)B_{+}^{*}(s)(\lambda_{\mathrm{c}}s + 1)^{m-n_1}} \tag{3}$$

where λ_{c} is an adjustable parameter for controller tuning, and $B_{+}^{*}(s)$ denotes the complex conjugate of $B_{+}(s)$, corresponding to all zeros in LHP. It can be easily verified that the above controller is biproper.

Assume that the process is located in the family of $\Pi = \{G : |G(j\omega) - G_{\mathrm{m}}(j\omega)|/|G_{\mathrm{m}}(j\omega)| \leqslant |\Delta_{\mathrm{m}}(j\omega)|\}$, where $\Delta_{\mathrm{m}}(j\omega)$ denotes the process multiplicative uncertainty. According to the small gain theory [5], the IMC system maintains robust stability if and only if

$$|\Delta_{\mathrm{m}}(j\omega)T(j\omega)| < 1, \quad \forall \omega \in [0, \infty) \tag{4}$$

where $T = G_{\mathrm{m}}C_{\mathrm{IMC}}$ is the closed-loop system transfer function for the nominal case ($G = G_{\mathrm{m}}$).