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Iterative learning control with Smith time delay compensator for batch processes

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Abstract

How to improve the control of batch processes is not an easy task because of modeling errors and time delays. In this work, novel iterative learning control (ILC) strategies, which can fully use previous batch control information and are attached to the existing control systems to improve tracking performance through repetition, are proposed for SISO processes which have uncertainties in modeling and time delays. The dynamics of the process are represented by transfer function plus pure time delay. The stability properties of the proposed strategies for batch processes in the presence of uncertainties in modeling and/or time delays are analyzed in the frequency domain. Sufficient conditions guaranteeing convergence of tracking error are stated and proven. Simulation and experimental examples demonstrating these methods are presented. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Iterative learning control; Batch processes; Smith predictor; Model uncertainty

1. Introduction

While continuous processing has always been considered the ideal method of operation of a chemical plant, there are a lot of low-volume and high-cost materials are obtained in batchwise form in many chemical and petroleum plants. Improved performance of batch processes is becoming necessary because of competitive markets. Even though there exists an important amount of literature referring to batch unit optimal control methods [1–3], these methodologies are rarely part of everyday industrial practice because of imperfect modeling, unmeasured variables and time delays. As a result of these issues, the degree of automation of many batch units is still very low.

The concept of iterative learning control has been presented by many researchers. Iterative learning control (ILC) provides a method for increase of control efficacy by taking advantage of the accumulation of batch-to-batch data. Many ILC algorithms have been proposed [4–12]. The usual approach of the existing works is to presume a specific learning control scheme in the time domain and then to find the required convergence conditions, and most of the works focuses on only finding open-loop control signals. In practice where unexpected disturbances are unavoidable, these algorithms may fail to work.

Very few results, up to now, on the ILC are for dynamics systems with time-delay. Lee et al. [13] proposed a feedback-assisted ILC for chemical batch processes, but this method is sensitive to process order and time delays, and the general stability analysis is not available. Hideg [14] investigated the possibility of divergence of an ILC for a plant with time-delay. Park et al. [15] designed an ILC algorithm for a class of linear dynamic systems with time-delay. However, only uncertainty in time-delay is considered in the existing literature.

In the present study, learning control algorithms together with a Smith predictor for batch processes with time delays are proposed and analyzed in the frequency domain. The dynamics of the process are represented by transfer function plus dead time. Perfect tracking can be obtained under certain conditions. Convergence conditions of the proposed methods are stated and proven. By using the past batch control information, the proposed ILC strategies are able to gradually improve

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performance of the control system. These results are evaluated through simulation as well as experiments.

2. System description

In this work, a SISO batch process is described by a transfer function $P_0(s)$ which is assumed to consist of a rational stable transfer function $P_0(s)$ and a dead time, θ. Thus, $P(s)$ is given by

$$P(s) = P_0 e^{-\theta s} \tag{1}$$

and a model of $P(s)$ is described by

$$\hat{P}(s) = \hat{P}_0 e^{-\hat{\theta} s} \tag{2}$$

where $\hat{P}_0$ is a model of P_0, and $\hat{\theta}$ is an estimate of θ, the dead time.

A common configuration of the control system with a Smith predictor is shown in Fig. 1, where r is the reference trajectory and $C(s)$ represents the transfer function of the primary controller which is usually taken to be a conventional PI or PID controller or any lead-lag network. It is well known that $C(s)$ permits higher gains to be used for the structure in Fig. 1. This increase in the permitted gains comes from the elimination of the dead time from the characteristic equation of the closed loop. When a perfect model is available, the overall transfer function, $G_0(s)$, from r to y is

$$T = \frac{C\hat{P}_0}{1 + C\hat{P}_0} \tag{3}$$

which is called the complementary sensitivity function. Correspondingly, the sensitivity function is

$$S = \frac{1}{1 + C\hat{P}_0}. \tag{4}$$

It can be seen that the characteristic equation does not contain dead time. Stability properties of the system for continuous systems in the presence of modeling errors have been studied by Palmor [16]. In this study, ILC strategies incorporating this structure will be analyzed and applied to batch processes.

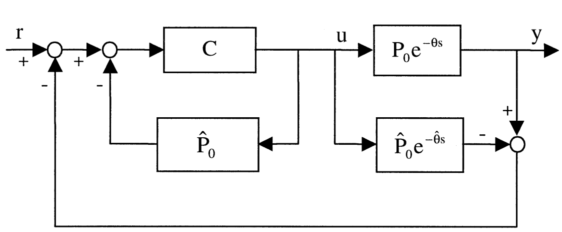

Fig. 1. A standard form of Smith predictor controller.

Perfect tracking of continuous process is generally impossible in practice because of modeling uncertainties, unmeasured disturbances and unreality of compensators. The repeating operations of batch process make it possible to reduce the tracking error gradually as the batch number increases. The objective of learning control is to progressively achieve a perfect tracking which may be written mathematically as

$$\lim_{k \to \infty} \|r - y_k\| = 0 \tag{5}$$

for an appropriate norm.

Note that (5) is defined over the time domain $[0, \quad T]$. If the process has a time delay θ, the associated time domain has to be shifted to $[\theta, \theta + T]$, and (5) becomes

$$\lim_{k \to \infty} \|r e^{-\theta s} - y_k\| = 0 \tag{6}$$

which is the best result we can obtain with feedback control.

3. ILC strategies with Smith time delay compensator

In this section, an ILC strategy for the case where both the transfer function and the time delay are unknown is considered. Fig. 2 is a block diagram of the ILC designed in this case and referred to as ILC-1, which is comprised of a iterative learning control law and a Smith predictor. The update law of the control signal is

$$u_k = u_{k-1} + C[r - (P_0 e^{-\theta s} + \hat{P}_0 - \hat{P}_0 e^{-\hat{\theta} s}) u_k]. \tag{7}$$

Multiplying P on both sides of (7) gives the following equation

$$y_k = \frac{1}{1 + C(P_0 e^{-\theta s} + \hat{P}_0 - \hat{P}_0 e^{-\hat{\theta} s})} y_{k-1} + \frac{C P_0 e^{-\theta s}}{1 + C(P_0 e^{-\theta s} + \hat{P}_0 - \hat{P}_0 e^{-\hat{\theta} s})} r. \tag{8}$$

If we define

$$e_k^1 = \frac{P_0 e^{-\theta s}}{P_0 e^{-\theta s} + \hat{P}_0 - \hat{P}_0 e^{-\hat{\theta} s}} r - y_k \tag{9}$$

then (8) can be rewritten as a recursion equation with respect to the tracking error

$$e_k^1 = Q_1(s) e_{k-1}^1 \tag{10}$$