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Enhancing trajectory tracking for a class of process control problems using iterative learning

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Abstract

A method of enhancing tracking in repetitive processes, which can be approximated by a first-order plus dead-time model is presented. Enhancement is achieved through filter-based iterative learning control (ILC). The design of the ILC parameters is conducted in frequency domain, which guarantees the convergence property in iteration domain. The filter-based ILC can be easily added to existing control systems. To clearly demonstrate the features of the proposed ILC, a water heating process under a PI controller is used as a testbed. The empirical results show improved tracking performance with iterative learning. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Enhance tracking; Filter-based iterative learning control; Frequency convergence analysis

1. Introduction

Trajectory tracking, whose primary control target is to track the a specified profile as tightly as possible in finite time interval, is very common in both process control and motion control problems, e.g. temperature control of a chemical reactor in pharmaceutic industry, or velocity control of an industrial robot in welding process. In practice the most widely used control schemes in industries are still PI or PID controllers with modifications, owing to the simplicity, easy tuning, and satisfactory performance (Sepehri et al., 1997; Isaksson and Graebe, 1999; Wang and Shao, 2000). On the other hand, many advanced control schemes have been proposed to handle complicated control problems. Nevertheless, it is still a challenging control problem when the perfect trajectory tracking is concerned, i.e. how to achieve satisfactory tracking performance when the process is under transient motion over the entire operation period. Most advanced control schemes can only achieve perfect tracking asymptotically—the initial tracking will be conspicuously poor within the finite interval. PI or PID control schemes in most cases can only warrant a zero steady-state error.

There are many industrial processes under batch operations, which by virtue are repeated many times with the same desired tracking profile. The same tracking performance will thus be observed, albeit with hindsight from previous operations. Clearly, these continual repetitions make it conceivable to improve tracking, potentially over the entire task duration, by using information from past operations.

To enhance tracking in repeated operations, ILC schemes developed hitherto well cater to the needs (Arimoto et al., 1984; Bien and Xu, 1998; Kuc et al., 1992; Lee and Bien, 1997; Lee et al., 1994; Longman, 1998; Moore, 1998; Phan and Juang, 1996; Lee et al., 2000; Wang, 2000). ILC uses repetitions as experience to improve tracking without exact system knowledge and becomes one of the most active fields in intelligent control and system control. ILC differers from most existing control methods in the sense that it exploits every possibility to incorporate past control information, such as tracking errors and control input signals, into the construction of the present control action (Xu et al., 2000). Numeric processing on those acquired signals yields a kind of new feed-forward compensation, which differs from most existing feed-forward compensations that are highly model based. Comparing with many feed-forward compensation schemes, ILC requirements are minimal—a memory storage for past data plus some simple data operations to derive the feed-forward signal. With its utmost simplicity, ILC can very easily be added on top of existing (predominantly PID batch) facilities without any hassle at all.

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In this paper, ILC is employed to enhance the performance of a kind of process dynamics, which can be characterized more or less by the first-order plus dead time (FOPDT) model. The approximated model is usually obtained from the empirical results. It has been shown that this approximation model, though very simple, stands near 60 years and is still widely adopted (Seborg et al., 1989). Based upon this FOPDT, the famous Zieger/Nichols tuning method (Ziegler and Nichols, 1942) was developed and nowadays become an indispensable part of control textbooks (Ogata, 1997).

However, when higher tracking performance is required, feedback and feed-forward compensations based on FOPFT model may not be sufficient due to the limited modeling accuracy. In such circumstance, ILC provides a unique alternative: reconstruct and capture the desired control profile iteratively through past control actions, as far as the process is repeatable over the finite time interval. In this paper, the filter-based learning control scheme is incorporated with PI control in order to improve the transient performance in time domain.

The filter-based ILC scheme is proven to converge to the desired control input in frequency domain within the bandwidth of interest. The bandwidth of interest can be easily estimated using the approximated FOPDT model. The proposed ILC scheme simply involves two parameters—the filter length and the learning gain, both can be easily tuned using the approximated model. Also, this scheme is practically robust to random system noise owing to its non-causal zero-phase filtering nature. A water heating plant is employed as a testbed to illustrate the effectiveness of the proposed filter-based learning scheme.

The paper is organized as follows. Section 2 formulates the control problem of FOPDT in general, and the modeling of a water heating plant in particular. Section 3 gives an overview of filter-based ILC with its convergence analysis in frequency domain. Section 4 details the controller design work and the experimental results. From these results, a modified ILC scheme with profile segmentation and feed-forward initialization, is used to improve tracking performance even further. Finally, Section 5 concludes the paper.

2. Problem formulation

2.1. FOPDT model and PID control

The FOPDT model, has been widely used in industries to approximate various kinds of type 0 processes

$$G(s) = \frac{K\mathrm{e}^{-\tau s}}{1 + sT_\mathrm{a}}, \tag{1}$$

where K is the plant steady-state gain, T_a is the apparent time constant and τ is the apparent dead time. There are mainly two reasons accounting for the popularity of FOPDT model. The first is its extremely simple structure associated with only three parameters which can be easily calculated through empirical tests, for example a simple open-loop step response (Ogata, 1997). The second is the well developed PI and PID autotuning rules which provide a simple and effective way for setting controller parameters (Ziegler and Nichols, 1942; Hang et al., 1991).

FOPDT model provides a very convenient way to facilitate the PI/PID controller setting, regardless of the existence of nonlinear factors, higher-order dynamics, or even distributed parametric dynamics, etc. In practice the FOPDT model based PI/PID control has been effectively applied to two kinds of control problems. One is the regulation problem where the objective is to maintain the operating point, and another is the set-point control problem where the objective is to achieve a pre-specified step response with balanced performance among settling time, overshoot and rising time. However, this simple control strategy, which is based on simple model approximation such as FOPDT, and simple control schemes such as PID, may not be suitable for more complicated control tasks with high tracking precision requirement. Consider a control target: tracking a temperature profile as shown in Fig. 1. This is the simplest trajectory consisting of two segments: a ramp and a level, starting at $t = 0$ and ending at $t = 3600$ s.

A few problems arise when such a trajectory tacking task is to be fulfilled. First, a single integrator is inadequate to follow a ramp signal. Adding more integrators will adversely degrade the system performance due to the extra phase lag. Second, even if the

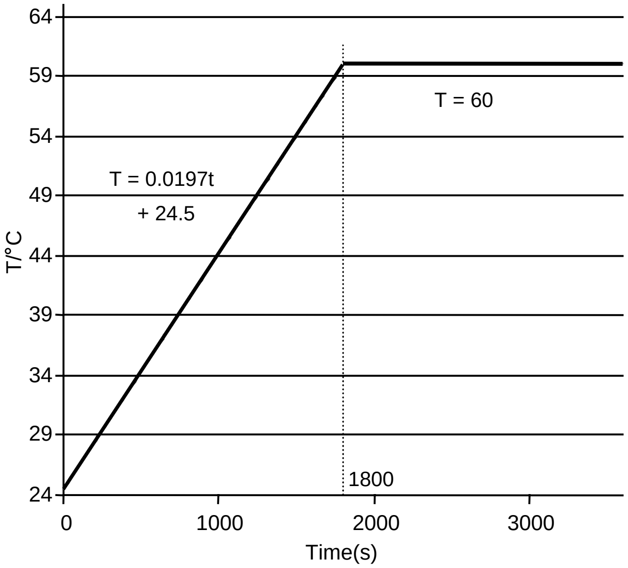

Fig. 1. Desired temperature profile.