Available online at www.sciencedirect.com
SCIENCE DIRECT®

Control Engineering Practice 13 (2005) 1455–1461

CONTROL ENGINEERING PRACTICE

www.elsevier.com/locate/conengprac

Iterative learning control for position tracking of a pneumatic actuated X–Y table

Chih-Keng Chen*, James Hwang

Department of Mechanical and Automation Engineering, Da-Yeh University, 112, Shan-Jiau Road, Changhua, Taiwan 515, ROC

Received 12 September 2003; accepted 22 December 2004
Available online 9 February 2005

Abstract

The iterative learning control (ILC) obtains the unknown information from repeated control operations. Meanwhile, the tracking error from previous stages is used as the correction factor for the next control action. Therefore, the ILC controller can make the system tracking error converge to a small region within a limited number of iterations. This study builds a proportional-valve-controlled pneumatic X–Y table system for performing position tracking control experiments. The experiments involve implementing the ILC controllers and comparing the results. The P-type updating law with delay parameters is used for both the x- and y-axes in the repetitive trajectory tracking control. Experimental results demonstrate that the ILC controller can effectively control the system and track the desired circular trajectory at different speeds. The control parameters are varied to investigate their effects on the ILC convergence.

Keywords: Proportional valve; Pneumatic system; Iterative learning control (ILC); Two-dimensional system; X–Y table

1. Introduction

The valve-controlled pneumatic system is a nonlinear system. The linearized models based on complicated procedures are required to apply the classical or modern controller design (McCloy & Martin, 1980; Watton, 1987). Owing to the air compressibility, the pneumatic system is highly nonlinear and temperature sensitive. The system parameters are sensitive to the changes in external load and temperature. Advanced controllers involving complicated computational procedures are frequently required. The modeling and control of a light-weight pneumatic robot system has been studied for the position tracking and end-effector force control (Bobrow & McDonell, 1998). This approach depends completely on the nonlinear dynamic model for the controller design. Meanwhile, the fuzzy and sliding surface control schemes are used for controlling the position of a propositional-valve-controlled pneumatic rodless cylinder (Renn, 2002).

Iterative linear control (ILC) was first proposed by Arimoto, Kawamura, and Miyazaki (1984). The PID-type learning algorithm was proposed to ensure tracking error convergence between the system output and a reference input. Theoretically, under the assumption of the same initial conditions, the tracking error should converge to zero with increasing number of iterations. Different learning control schemes are also provided by Amann, Owen, and Roger (1996), Bien and Xu (1998), Kurek and Zaremba (1993), Moore (1992) and Moore and Xu (2000) for the comparison and improvement of learning speed and control accuracy. The ILC system operates in two dimensions, time and trial number. This complicated two-dimensional (2-D) analysis system has previously been studied by Arimoto et al. (1984), Padieu and Su (1990), and Geng, Lee, Carroll, and Haynes (1991). Some practical implementations of ILC controller have been applied to position control of

*Corresponding author. Tel.: +886 4 8511888x2108; fax: +886 4 8511224.
E-mail address: ckchen@mail.dyu.edu.tw (C.-K. Chen).

0967-0661/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conengprac.2004.12.015

mechanical systems (Barton, Lewin, & Brown, 2000; Chen & Zeng, 2003).

This study uses a P-type ILC algorithm with time delay parameter to control a pneumatic X–Y table so that it follows the desired circular trajectory. The proportional-valve-controlled pneumatic X–Y table system is established for the position tracking control experiments. The pneumatic cylinders controlled by the proportional valves are sensitive to external loads and essential nonlinear systems. Thus, the constant-gain linear controller, such as PID, cannot track the position reference input accurately. Section 2 discusses the scheme of the P-type ILC controller. Meanwhile, the experimental apparatus used for this research is designed and shown in Section 3. The ILC controllers are implemented in the pneumatic platform to verify the tracking ability of the system given different reference inputs, as shown in Section 4. The experimental results using the traditional PID and ILC controllers are presented to provide a comparison. Finally, the delay time parameter is adjusted to seek to reduce the mean square error of tracking control.

2. ILC controller

ILC uses the error information from the current control trial to update the control signal for future trials to reduce the tracking error between the output and a reference input. Many learning schemes have been developed for linear and nonlinear systems to ensure tracking error convergence (Kurek and Zaremba, 1993). Consider the following nonlinear time-invariant discrete-time system:

$$\mathbf{x}(t+1) = \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)),$$
$$\mathbf{y}(t) = \mathbf{h}(\mathbf{x}(t)), \tag{1}$$

where $\mathbf{x} \in \mathbf{R}^n$ denotes a state vector, $\mathbf{u} \in \mathbf{R}^m$ represents an input vector, $\mathbf{y} \in \mathbf{R}^p$ is the output vector and $\mathbf{f}(\mathbf{x})$ and $\mathbf{h}(\mathbf{x})$ are vectors with appropriate dimensions. The problem can be formulated as follows. Given system (1) with initial condition $\mathbf{x}(0) = \mathbf{x}_0$, reference output $\mathbf{y}_d(t)$ and the tolerance $\varepsilon \geqslant 0$, the control sequence $\mathbf{u}(t)$ is determined by using the learning algorithm such that the system output follows the reference trajectory under the condition $\left|\mathbf{y}_d(t) - \mathbf{y}(t)\right| < \varepsilon$. The reference output $\mathbf{y}_d(t)$ remains unchanged for different trials; however, $\mathbf{u}(t)$ is updated via the learning rule between two iterations.

In 2-D representation, the ILC system dynamics can be discussed along two directions: time t and number of iterations k. The first direction represents the system dynamics in time, namely, the time response. The second direction reflects the dynamics of the iterative learning. In the 2-D representation system, the tracking error can be defined as

$$\mathbf{e}(t,k) = \mathbf{y}_d(t) - \mathbf{y}(t,k). \tag{2}$$

The simplest learning update law can be expressed as

$$\begin{aligned}\mathbf{u}(t,k+1) &= \mathbf{u}(t,k) + \mathbf{K}\mathbf{e}(t+1,k)\\ &= \mathbf{u}(t,k) + \Delta\mathbf{u}(t,k+1),\end{aligned} \tag{3}$$

where $\Delta\mathbf{u}(t,k+1)$ denotes the updating control signal for trial $k+1$, $\mathbf{u}(t,k)$ represents the input $\mathbf{u}$ in the kth learning iteration, $\mathbf{K} \in \mathbf{R}^{m\times p}$ is the learning gain matrix and $\mathbf{u}(t,k+1)$ denotes the input for the $(k+1)$th trial. Eq. (3) is also termed the P-type learning law, since the revision in the control signal is only proportional to the tracking error. Since the desired trajectory and system output differ between trials, the error can be used to update the control input at the next trial to satisfy the tolerance requirement.

The learning gain can affect system stability and error convergence. The role of learning gain $\mathbf{K}$ in Eq. (3) is analogous to the proportional gain in the PID controller. Larger gain can increase the error convergence speed, but causes severe error oscillations within a certain range. In contrast, small learning gain requires more iterations to fulfill the error requirement. Adaptive learning gain has been proposed as a method of accelerating the convergence speed faster (Geng et al., 1991; Barton et al., 2000).

When the learning rule considers system delay, the "future" error $\mathbf{e}(t+1+d,k)$ can be used to update the signal for the $(k+1)$th trial, where d denotes the time delay. The learning control rule (3) can be modified as follows:

$$\begin{aligned}\mathbf{u}(t,k+1) = \mathbf{u}(t,k) + \mathbf{K}[\mathbf{y}_d(t+1+d)\\ - \mathbf{y}(t+1+d,k)].\end{aligned} \tag{4}$$

That is, Eq. (4) uses the error in the last trial, with d sampling periods delayed from current time, to update the control signal. The real delayed time is $dt = t_s \times d$, where t_s denotes the system sampling time. The experimental results shown later indicate that the tracking performance can be improved through proper selection of the delay parameter d. However, this approach can only identify the control sequence $\Delta\mathbf{u}(t,k)$, $t = 0, 1, \ldots, N-1-d$ from the tracking error $\mathbf{e}(t,k)$ for $t = d+1, d+2, \ldots, N$. To generate the last d control signals $\mathbf{u}(t,k+1)$, $t = N-d, \ldots, N-1$, the errors $\mathbf{e}(t,k)$, $t = 1, 2, \ldots, d$ are used to extend the error sequence to the next cycle. That is, $\mathbf{e}(t+N,k) = \mathbf{e}(t,k)$ is assumed for $t = 1, 2, \ldots, d$ to compute the last d control signals since the input is periodic.

3. Experimental apparatus

The experimental apparatus, as illustrated in Fig. 1, is a proportional-valve-controlled pneumatic X–Y table