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Analysis and comparison of iterative learning control schemes

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Abstract

Iterative learning control (ILC) schemes can be classified into the previous cycle learning (PCL), the current cycle learning (CCL) and the synergy—previous and current cycle learning (PCCL). In this work, we first present the configurations of various ILC schemes and the corresponding convergence conditions associated with each configuration. As a result of comparison, the PCCL scheme shows the ability of outperforming the PCL and CCL schemes owing to its underlying feature of two degrees of freedom design. Subsequently, we focus on two practical PCCL schemes with analysis and comparisons in frequency domain, substantiate the difference in the learning updating mechanisms, and in the sequel exploit the circumstances where one PCCL scheme can outperform the other. Based on system Bode plots, we can easily check the learning convergence condition, the complementary property of feedback and feedforward compensation, and which PCCL scheme can perform better. For the purpose of comparison and verification, both schemes are applied to a real-time ball-and-beam system.

Keywords: Iterative learning; Feedforward; Feedback; Property comparison; Experimental verification

1. Introduction

Numerous iterative learning control (ILC) schemes have been developed in the past two decades with the aim to improve the control performance over a fixed time interval iteratively whenever the control task repeats (Arimoto et al., 1984; Moore et al., 1992; Moore, 1993; Jang et al., 1995; Owens et al., 1996). From practical point of view, many real control systems are modeled and designed in frequency domain (Barton et al., 2000). In such circumstance, the process model is obtained in frequency domain either from a transfer function, or directly from a Bode plot characterizing the process. ILC, analogous to other control methods, needs frequency domain control design and property analysis in order to meet real life requirements (Chen and Wen, 1999; Xu et al., 2001, 2002; Hu et al., 2001; Norrlof and Gunnarsson, 1999; Moon et al., 1996; Ahn et al., 1995; Lee et al., 1994).

In this work we discuss the schematics of ILC configurations in general, discuss two typical ILC schemes with previous and current cycle learning in particular. We first discuss the representative configurations of several ILC schemes which can be classified into the previous cycle learning (PCL), the current cycle learning (CCL), the previous and current cycle learning (PCCL), as well as PCL with the cascaded structure. The convergence conditions associated with each learning configuration are derived in frequency domain. Next we show, from a frequency perspective, a highly desired property possessed by the PCCL scheme—the complementary role of feedback and learning based feedforward. Being simple and widely applied, PCCL schemes possess the same feedback mechanism but different learning mechanisms. Then we focus on two practical PCCL schemes. In the first step we derive the learning convergence conditions. The difference in learning mechanisms will result in different convergence conditions. In the second step the two PCCL schemes are compared in terms of the convergence speed, which depends on the system types and relative degrees.

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Finally two PCCL schemes are implemented on a ball-and-beam platform with detailed discussions on the ILC design and analysis. We will analyze, compare and test the two PCCL schemes in frequency domain using Bode and Nyquist plots intensively. This part serves to provide an illustrative example to researchers and engineers on how to implement ILC schemes, in the sequel shorten the gap between theoretical study and practical implementation of ILC. The experimental results clearly verifies the validity of the conclusions made in the analysis and comparison of the two PCCL schemes.

The paper is organized as follows. In Section 2, the configurations of ILC schemes and several convergence conditions are discussed. In Section 3, the schematics of the two PCCL schemes are discussed and the comparison studies are conducted for certain circumstances. In Section 4, the implementation of two PCCL learning control schemes for a real-time ball-and-beam system is demonstrated with experimental results.

2. The configurations of ILC

ILC is a relatively new control methodology to perform perfect tracking for periodical reference signals or rejecting periodical disturbances. Comparing to the classical feedback and feedforward control methods, the ILC makes full use of control signals obtainable from previous iterations or operation cycles. The repeatability of the task determines the learnability of the ILC.

Most ILC schemes can be classified into the current cycle learning (CCL) scheme, the previous cycle learning (PCL) scheme and the integrated one (PCCL), as shown below.

2.1. The previous cycle learning scheme (PCL)

The configuration of a PCL scheme is shown in Fig. 1. Here the subscript i denotes the ith iteration. Hence $y_{d,i}$, y_i, u_i and e_i denote the reference signal, output signal, control signal, and error signal, respectively, at the ith iteration. G_p and G_{ff} denote the transfer functions of the plant and the control compensator, respectively. In cases the system perform the same control task, $y_{d,i+1} = y_{d,i}$. In this research work a repeated control task is assumed. The MEM labeled with y, y_d and u are memory arrays storing system signals of the current cycle ($i+1$th iteration) to be used in the next learning cycle (iteration).

According to the PCL configuration shown in Fig. 1,

$$y_i = G_p u_i,$$
$$e_i = y_d - y_i,$$
$$u_{i+1} = u_i + G_{ff} e_i. \quad (1)$$

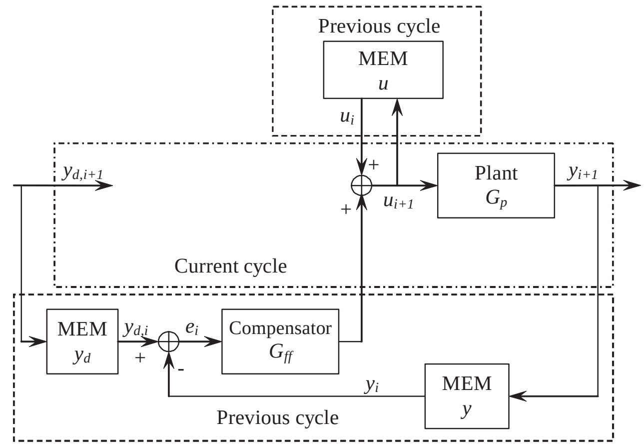

Fig. 1. The schematics of PCL.

Eq. (1) is the PCL updating law. It is called previous cycle learning simply because only the previous cycle control signals u_i and error signals e_i are used to form the current cycle control input u_{i+1}.

The learning convergence condition for PCL can be derived by substituting the learning control law into the formula of the current cycle tracking error

$$\begin{aligned} e_{i+1} &= y_d - y_{i+1} \\ &= y_d - G_p u_{i+1} \\ &= y_d - G_p(u_i + G_{ff} e_i) \\ &= (1 - G_p G_{ff}) e_i \end{aligned}$$

$$\Rightarrow \frac{e_{i+1}}{e_i} = 1 - G_p G_{ff}$$

$$\Rightarrow \left\| \frac{e_{i+1}}{e_i} \right\| = \|1 - G_p G_{ff}\| \leqslant \rho < 1, \quad (2)$$

where $\|G\| = |G(j\omega)|$ denotes the magnitude of the transfer function at a specified frequency ω. The norm $\|\cdot\|$ is defined as infinity norm for all frequencies $\leqslant \omega_b$ and ω_b is the bandwidth that ILC schemes can be applied. Clearly, as far as the tracking error signals of the 1st iteration, e_1, is finite, then $\|e_i\| \leqslant \rho^i \|e_1\| \to 0$ as $i \to \infty$. It can also be seen that, for a specified threshold of the tracking error, a smaller initial error profile e_1 may expedite the learning process.

2.2. The current cycle learning scheme (CCL)

The configuration of a CCL scheme is shown in Fig. 2.

According to the CCL configuration shown in Fig. 2, the updating law of the CCL scheme is

$$u_{i+1} = u_i + G_{fb} e_{i+1},$$

where the G_{fb} is the transfer function of the compensator which is, in fact, a feedback controller. It is called current cycle learning because the current cycle tracking