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Iterative learning control for a non-minimum phase plant based on a reference shift algorithm

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Abstract

In order to improve the tracking performance of a non-minimum phase plant, a new method called the reference shift algorithm has been developed to overcome the problem of output lag encountered when using traditional feedback control combined with basic forms of iterative learning control. In the proposed algorithm a hybrid approach has been adopted in order to generate the next input signal. One learning loop addresses the system lag and another tackles the possibility of a large initial plant input commonly encountered when using basic iterative learning control algorithms. Simulations and experimental results have shown that there is a significant improvement in tracking performance when using this approach compared with that of other iterative learning control algorithms that have been implemented on the non-minimum phase experimental test facility.

Keywords: Iterative learning control; Reference shift; Non-minimum phase plant

1. Introduction

Iterative learning control is a technique applicable to systems operating in a repetitive mode with the additional requirement that a specified output trajectory $r(t)$ defined over a finite interval $[0, T]$ is followed to a high precision. Examples of such systems are robot manipulators that are required to repeat a given task to high precision, chemical batch processes or, more generally, the class of tracking systems. Motivated by human learning, the basic idea of iterative learning control is to use information from previous executions of the task in order to improve performance from trial to trial in the sense that the tracking error is sequentially reduced.

The original work in this area can be traced back to Arimoto, Miyazaki, and Kawamura (1984). For example, suppose that the signal to be tracked over $[0, T]$ on trial $k>0$ then the basic P-type ILC algorithm consists of an update incorporating the error from the previous trial of the form

$$u_{k+1}(t) = u_k(t) + Le_k(t), \quad (1)$$

where L is the proportional scalar learning gain, $u_k(t)$ is the control signal applied on trial k, and the tracking error on this trial is given by $e_k(t) = r(t) - y_k(t)$ where $y_k(t)$ denotes the corresponding plant trial output. Many other simple structure ILC algorithms have also been considered such as those termed the D-type, delay type (see, for example, Barton, Lewin, & Brown, 2000) and phase-lead algorithms (see, Freeman, Lewin, & Rogers, 2005; Wang & Longman, 1996). Moreover, ILC algorithms have moved beyond these relatively simple structure types and now encompass a wide range of (linear and nonlinear) plant models and control law structures (for examples of nonlinear applications see Hakvoort, Aarts, van Dijk, & Jonker, 2007; Heertjes & Tso, 2007). In terms of actual application, however, it is clear that the ILC law with the simplest structure which can meet the performance requirements should be used.

In some cases, the development of the algorithm has been accompanied by experimental studies but only a

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somewhat limited amount of work has been directed at ILC for plants which can be adequately modelled by a linear but non-minimum phase model. This is despite the fact that such models arise in many relevant applications areas and also there are theoretical results which show that obtaining high performance from ILC applied to such plants could well be problematic (Amann & Owens, 1994).

Given the statement above about the complexity of the algorithm for actual implementation, this paper focuses on applying the simple phase-lead law and attempting to overcome the difficulties that have previously been encountered when using it. A specially constructed experimental non-minimum phase linear system is used and the focus of the paper is on the practical issues involved with achieving a high level of tracking performance whilst applying an intuitively simple ILC algorithm. For this reason, analysis is restricted only to showing that the algorithm used satisfies a well known convergence criterion, whilst the major contribution of the paper lies in the experimental results and associated discussion which examine the effect of filtering and compare the present algorithm with a well established but far more complex model-based ILC law. Such information informs the controller design process. Justification for adopting the intuitively simple approach is provided by results that show that it achieves faster convergence and less fluctuation in tracking error than other approaches.

2. Experimental test facility

Limited experimental evidence is available on the application of ILC to non-minimum phase plants. One approach is described in Markusson, Hjalmarsson, and Norrlof (2001) but this encountered significant challenges due to need to use the inverse of the plant model. Such systems will arise in applications, however, and hence there is a clear need to develop efficient ILC algorithms for such cases if this technique is to achieve the widest possible impact. To this end an experimental test facility has been constructed to evaluate ILC (and also repetitive) schemes (see, Freeman et al., 2005 for details) when the plant transfer function has a right-half plane zero. It consists of a rotary mechanical system of inertias, dampers, torsional springs, a timing belt, pulleys and gears. The non-minimum phase characteristic is achieved by using the arrangement shown in Fig. 1(a), where θ_i and θ_o are the input and output positions, J_r and J_g are inertias, B_r is a damper, K_r is a spring and G_r represents the gearing. A further spring–mass–damper system is connected to the input in order to increase the relative degree and complexity of the system. A 1000 pulse/rev encoder records the output shaft position and a standard squirrel cage induction motor drives the load. The nominal continuous time plant transfer function has been identified from frequency response data (using the Bode gain plot approximation and some data conditioning) as

$$G_0(s) = \frac{1.202(4-s)}{s(s+9)(s^2+12s+56.25)}. \tag{2}$$

A PID loop around the plant is used in all the tests since this has been found to produce a reasonable response over the first trial. The PID gains used in all test results given here were $K_p = 137$, $K_i = 5$ and $K_d = 3$ (proportional, integral and derivative, respectively). The resulting closed-loop system constitutes the system to be controlled, P, and a constant sampling period, T_s, of 1 ms is used.

Previous work (Freeman et al., 2005) (based on a significant number of experimental runs) has established that a simple phase-lead algorithm with a carefully selected filter can be used to successfully control the non-minimum phase plant considered here. An intuitive justification for using this update arises from observing that a typical feature of non-minimum phase plants is a pronounced lag in the output in response to an arbitrary input. To find a single time-delay representative of this effect for a given input signal and plant, the input can be shifted in time relative to the output and a minimum norm of the difference sought with respect to this shift. Intuitively the length of this time shift could be used as a parameter, τ, in an expression modelling the plant as a simple time delay. This model would take the form $G(z) = \gamma z^{-\tau/T_s}$, where γ is a scalar gain, and the corresponding plant inverse is given by $G^{-1}(z) = \gamma^{-1} z^{\tau/T_s}$. When used in the z-transformed ILC inverse algorithm (see, Ratcliffe et al., 2004 for details) this yields

$$u_{k+1}(z) = u_k(z) + G^{-1}(z)e_k(z) = u_k(z) + Lz^{\tau/T_s}e_k(z) \tag{3}$$

which corresponds to the phase-lead update

$$u_{k+1}(t) = u_k(t) + Le_k(t+\tau) \tag{4}$$

with $L = \gamma^{-1}$. Since the reference is defined over $[0, T]$ and $e_k(t+\tau)$ is defined over $[-\tau, T-\tau]$, application of the algorithm has involved discarding the error over the period

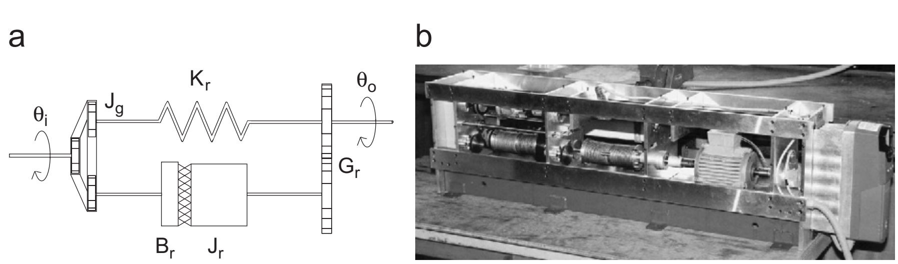

Fig. 1. The non-minimum phase plant experimental test facility. (a) Non-minimum phase section. (b) Non-minimum phase test facility.