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A novel design strategy for iterative learning and repetitive controllers of systems with a high modal density: Theoretical background

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ABSTRACT

This paper discusses the design and application of iterative learning control (ILC) and repetitive control (RC) for high modal density systems. Typical examples of these systems are structural and acoustical systems considered in active structural acoustic control (ASAC) and active noise control (ANC) applications. The application of traditional ILC and RC design techniques, which are based on a parametric system model, on systems with a high modal density has several important drawbacks: the design procedure is complex, the controllers require much computational power and the robustness of the controllers is low. This paper describes a novel strategy to design noncausal ILC and RC filters, which is especially suited for high modal density systems. Since it does not require a parametric system model, the novel strategy avoids several drawbacks of the traditional techniques: no cumbersome parametric model estimation is required; the ILC and RC controllers are robust to small changes of the poles and zeros of the controlled system; and the complexity of the ILC and RC control filters is restricted. A crucial element in the proposed strategy is the noncausal filtering in the ILC and RC controllers, which requires the availability of a trigger signal to announce a new ILC trial or RC period in advance. A numerical validation on a simulation model proves the potential of the developed strategy.

1. Introduction

Iterative learning control (ILC) is a well-known technique to increase the tracking accuracy of a system repeating a given operation, or to suppress a repetitive disturbance acting on a system [1]. The idea is to adjust the control signal by using experience from one trial in order to improve the performance in the next trial. Repetitive control (RC), which is a control technique closely related to ILC, is suitable for tracking periodic signals as well as for suppressing periodic disturbances: the information from previous periods is used to update the control input at the current period in order to enhance the performance [2]. While an ILC algorithm operates repeatedly in open loop during a finite time interval to control discrete disturbances or to follow reference trajectories, a RC algorithm is continuously active and is actually a feedback algorithm.

The origin of the ILC and RC strategies lie in the field of robotics and motion control, where often repetitive or periodic reference trajectories have to be tracked [3,4]. ILC and RC have also been used successfully in other research domains:

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Nomenclature

$d(k)$	disturbance signal
i	trial index of the ILC controller
k	index of discrete time signals
$L(q)$	discrete ILC and RC learning filter
p	number of discrete samples in the fundamental period of a RC controller
P	controlled plant
q	forward shift operator/scalar value of control filter Q
$Q(q)$	discrete ILC and RC learning filter
T_s	discrete sample period
$u(k)$	control input
$y(k)$	error signal
z	discrete-time Laplace variable
ω	frequency (rad/s)
$A(z)$	Laplace transform of system $A(q)$
$A(\omega)$	discrete Fourier transform of system $A(q)$

control of chemical processes [5], durability test rigs for vibration tests in automotive industry [6–8], reduction of waveform distortion in PWM inverters [9]. In most of these conventional applications, systems with a relatively limited number of degrees of freedom are studied. However, the applicability of ILC and RC to more complex systems with a high modal density has recently also been demonstrated, e.g. ILC and RC have been successfully applied in active noise and active structural acoustic control [10,11].

The first ILC schemes consist of simple tunable PID-type learning filters, which process the error obtained during the previous trial [3,12]. To improve performance and to apply ILC to more complex systems, advanced design approaches have been developed such as an inverse model-based approach [13], an optimization-based approach [14] and a frequency-domain approach [15]. These approaches are only suited to control systems with a low modal density in the controlled frequency range, because they rely on a parametric system model. These models are difficult to estimate if the system has a high modal density. In addition, for systems with low damping these models are very sensitive to parameter changes and hence the controllers that rely on these models exhibit a low robustness. Therefore, this paper presents a novel frequency-domain approach, dedicated to the design of ILC controllers for the typical systems considered in ASAC and ANC; high modal density systems with lowly damped complex poles and zeros, possibly exhibiting a time delay. The dynamics of the considered systems are supposed to be time-invariant although the design approach is robust to small variations of the system's poles and zeros. The proposed design strategy is a four step procedure, which allows to make a tradeoff between performance and robustness. Since the procedure is directly based on a frequency response measurement instead of on a parametric model, the robustness can easily be assessed. The resulting controllers can increase the damping of the resonance frequencies of the controlled system and hence are favorable for acoustic and vibration control. Finally, in order to get the maximum advantage from ILC and RC, the presented approach extensively exploits the possibilities of noncausal filtering. Therefore, an accurate trigger signal, which announces a new ILC trial or RC period a constant time in advance, is supposed to be available.

The paper is organized as follows; after an introduction to ILC and RC, the developed design procedure is presented in Section 3. In Section 4, this strategy is adapted to the specific properties of RC systems. The main difference between the ILC and RC strategy lies in the implementation of the control filters. While in ILC a lot of future time samples are available, in RC only a limited number of future time samples can be processed. Consequently, the anticausal control action will be restricted in the case of RC. In the last section of the paper, the ILC and RC design techniques are validated on a simulation model.

2. Theoretical background

This section briefly discusses the theoretical background of ILC and RC. The similarities and differences between both techniques are highlighted. The general ILC control scheme for a linear time-invariant and causal SISO system $P(q)$ (with q the forward shift operator) is shown in Fig. 1. Since in ASAC and ANC applications, the goal is to reduce a certain error signal, the scheme lacks a reference signal (reference is zero). A linear, first-order ILC updating formula is applied to calculate the control input $u_i(k)$ at trial i based on the control input $u_{i-1}(k)$ and error $y_{i-1}(k)$ at trial $i-1$:

$$u_i(k) = Q(q)u_{i-1}(k) - L(q)y_{i-1}(k), \tag{1}$$

with $Q(q)$ and $L(q)$ the learning filters.

For these systems, a criterion for monotonic convergence and the final value of the error can be expressed in the frequency-domain [1,15]. Monotonic convergence of an ILC algorithm is guaranteed if a monotonic decay in the iteration domain of all the frequency components of the error signal is achieved by the algorithm:

$$|Q(\omega) - L(\omega)P(\omega)| < 1 \quad \forall\omega, \tag{2}$$

with $Q(\omega)$, $L(\omega)$ and $P(\omega)$ the discrete frequency response functions of $Q(z)$, $L(z)$ and $P(z)$. Smaller values of $|Q(\omega) - L(\omega)P(\omega)|$ correspond to an increased convergence speed and provide a larger robustness margin.