Annual Reviews in Control 000 (2016) 1–14

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Review

Tutorial review on repetitive control with anti-windup mechanisms

Liuping Wang

School of Electrical and Computer Engineering, RMIT University, Melbourne, Victoria 3000, Australia

A R T I C L E I N F O

Article history:
Received 31 May 2016
Revised 20 September 2016
Accepted 21 September 2016
Available online xxx

Keywords:
Repetitive control
Reference following
Disturbance rejection
Anti-windup mechanisms
Fourier analysis

A B S T R A C T

In many control system applications, tracking a periodic reference signal or rejecting a disturbance signal with a limited frequency band is a necessary task. Repetitive control systems are designed to perform such tasks. Because the repetitive control systems by nature have introduced unstable controller structures, control signal amplitude constraints commonly encountered in control system applications need to be considered with special care. Otherwise, the repetitive control system could become unstable when the control signals became saturated. Using the same framework of Model Predictive Control (MPC), but without the cost of online optimization that usually occurs in the MPC algorithms, this paper shows the design and implementation procedures of repetitive control of multi-input and multi-output systems with anti-windup mechanisms. Furthermore, by using Fourier analysis of a reference signal or a disturbance signal, the structure of a repetitive control system is determined. Simple and complex simulation examples are used to illustrate the procedures of design and implementation.

1. Introduction

Disturbance rejection and reference following are the main control objectives in feedback control applications. It is well understood that if the reference signal is piece-wise constant and the disturbance signal predominantly contains low frequency components, an integrator ($\frac{1}{s}$) is commonly embedded in the controller structure to achieve the control objectives (Astrom & Murray, 2008; Goodwin, Graebe, & Salgado, 2000; Morari & Zafiriou, 1989; Wang, 2009; Wang, Chai, Yoo, Gan, & Ng, 2015). In many other control applications, the physical system encounters periodic reference signals or bandlimited disturbance signals. For these systems, the controllers with embedded integrators no longer offer effective solutions for reducing the closed-loop feedback errors in the steady-state operation.

Repetitive control systems are the classical approach to control systems with periodic exogenous signals. Originated from the seminal papers by Inoue, Nakano, Kubo, Matsumoto, and Baba (1981); Nalano and Hara (1986), and Hara, Yamamoto, Omata, and Nakando (1988), the repetitive control systems embed the Laplace transfer function model $\frac{1}{1-e^{-Ts}}$ into the controller structure for asymptotic tracking of a periodic signal with period T. The transfer function $\frac{1}{1-e^{-Ts}}$ is regarded as the signal generator for a periodic signal with known period T. As pointed out in Hara et al. (1988), this irrational transfer function factor has an infinite number of equally spaced poles on the imaginary axis at $0, \pm j\frac{2\pi}{T}, \ \pm j\frac{4\pi}{T}, \ldots, \pm j\frac{k2\pi}{T}, \ldots$. Hence according to the internal model principle (Francis & Wonham, 1976), the desired properties for reference following and disturbance rejection of the signal with the same period T can be achieved in a stable closed-loop control system. Even though the repetitive control systems were derived in the continuous-time domain, it is the discrete-time version that has offered advantageous platforms for digital implementations (Longman, 2000; Wang, Gao, & Doyle, 2009). The signal generator in discrete-time for a periodic signal is $\frac{1}{1-z^{-N}}$, where N is the number of samples within a period. For the discrete-time case, the irrational transfer function e^{-Ts} is replaced by z^{-N} where $N = \frac{T}{\Delta t}$ and Δt is the sampling interval. It is interesting to note that in the frequency domain, defining the fundamental frequency $\omega_d = \frac{2\pi}{N}$, the magnitude of the signal generator $|\frac{1}{1-e^{-jN\omega}}| \rightarrow \infty$ at $\omega = 0, \ \omega = \pm\omega_d, \ \pm 2\omega_d, \ \ldots, \ \pm\frac{N-1}{2}\omega_d$ assuming that N is an odd number.

The novelty of using the factor $\frac{1}{1-e^{-Ts}}$ or $\frac{1}{1-z^{-N}}$ for repetitive control system lies in their easy realizations through a positive feedback configuration (Hara et al., 1988). However, these factors are ideal in theory. In practice, due to the difficulties in finding the stabilizing controllers, a cut-off filter, $q(s)$ in continuous-time or $Q(z)$ in discrete-time, was used, leading to the modified repetitive control systems with the transfer functions expressed as $\frac{1}{1-q(s)e^{-Ts}}$ in the continuous-time or $\frac{1}{1-Q(z)z^{-N}}$ in the discrete-time. Figs. 1 and 2 show the essential controller structures for both continuous-time and discrete-time repetitive control systems. In both control system configurations, after incorporating the signal generators,

E-mail address: liuping.wang@rmit.edu.au

http://dx.doi.org/10.1016/j.arcontrol.2016.09.016
1367-5788/© 2016 Published by Elsevier Ltd on behalf of International Federation of Automatic Control.

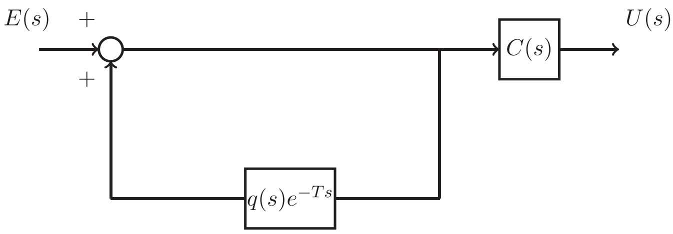

Fig. 1. Realization of continuous-time repetitive control system.

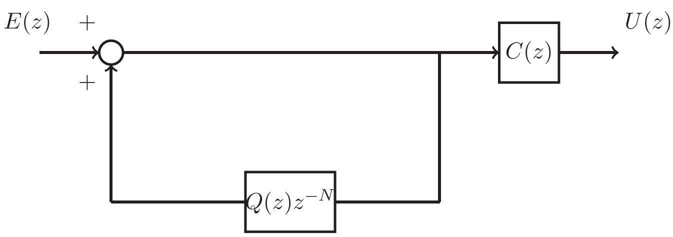

Fig. 2. Realization of discrete-time repetitive control system.

stabilization controllers $C(s)$ or $C(z)$ are required to produce stable closed-loop systems. From a historical perspective, at the time when the computational cost was expensive, an easy implementation of repetitive control system paved the way for its wide applications.

Over the past several decades, repetitive control systems have gained acceptance in the control engineering community and have found many applications. This type of control systems has been further extended into iterative learning control and run-to-run control. The survey papers and books are a good starting point for this subject (see Longman, 2000; Moore, 2012; Rogers, Galkowski, & Owens, 2007; Rogers & Owens, 1992; Wang et al., 2009). The most concentrated areas of applications are in process control and the control of electrical drives and power converters. The applications in process control include (Chin, Qin, Lee, & Cho, 2004; Lee, Lee, & Kim, 2000; Lee, Natarajan, & Lee, 2001; Lee, Bang, Yi, Son, & Yoon, 1996; Liu, Gao, & Wang, 2010). In electrical drive and power converter control, following a sinusoidal reference input signal or suppressing unwanted harmonic disturbances are important control objectives (Chai, Wang, & Rogers, 2013; Gan & Qiu, 2004; Tzou, Ou, Jung, & Chang, 1997; Wang et al., 2015; Zhang, Kang, Xiong, & Chen, 2003; Zhou, Wang, Zhang, & Wang, 2009). The repetitive controllers in the power electronic applications are also called resonant controllers. Examples of resonant controllers include the proportional-resonant controller for grid-connected voltage-source converters discussed in Teodorescu, Blaabjerg, Liserre, and Loh (2006), the PI-resonant controller in Liserre, Teodorescu, and Blaabjerg (2006) and the adaptive resonant controller in Timbus, Ciobotaru, Teodorescu, and Blaabjerg (2006).

This tutorial paper will focus on the design and implementation of discrete-time repetitive control systems. There are three aspects of the repetitive control systems that could be improved. Firstly, the repetitive controller order is too high (at least Nth order due to the embedded signal generator) causing complications in the implementations due to noise and model uncertainty. Secondly, because the repetitive controllers have unstable poles embedded in their structures, when the control signals are saturated, anti-windup mechanisms are required. This aspect is particularly important for practical applications as the control signal amplitude constraints are necessary for protecting the equipment. Thirdly, the transfer function based design was convenient for frequency response analysis, but it is difficult to extend the design methodologies to a multi-input and multi-output system. The first two issues imply that a repetitive controller may work perfectly for a design model, however, it may fail to produce a stable closed-loop system for the actual plant when it is implemented.

Recent advances in repetitive control systems have effectively addressed these three issues (Wang, Chai, Rogers, & Freeman, 2012; Wang, Freeman, & Rogers, 2013; 2016; Wang, Gawthrop, Owens, & Rogers, 2010; Wang & Rossiter, 2008) via the predictive control platform. The essence of the new developments is centered at modeling the reference signals using frequency sampling filter models (Wang & Cluett, 2000) and identifying the dominant frequencies required for the design of a repetitive control system. In a similar platform as model predictive control, multi-input and multi-output repetitive control systems are designed and implemented with operational constraints. The new repetitive control systems have been successfully implemented and experimentally tested on a robotic arm with two degrees of freedom (Wang et al., 2013; 2016) and an industrial electrical drive (Chai et al., 2013), and a power converter (Wang et al., 2015).

This tutorial paper gives detailed descriptions on the design and implementation of the new repetitive control systems. Recognizing that the core computational algorithm of model predictive control requires online optimization, which is more demanding in the implementation, this paper avoids that requirement by proposing a closed-form solution with anti-windup mechanisms. The remainder of this paper is organized as follows. In Section 2, a simple motivational example is used to demonstrate that a traditional repetitive control system becomes unstable when the control signal repeatedly reaches saturation limits, and how the proposed approach produces the stable closed-loop system using the anti-windup mechanism. In order to reduce the order of the repetitive controller, the frequency contents of the reference signal or the disturbance signal need to be analyzed to determine the dominant components. In Section 3, a periodic signal is firstly written in terms of the frequency sampling filter (FSF) model, where the model coefficients are the Fourier coefficients, and the signal generator for the periodic signal is the common denominator of the FSF model. To reduce the order of the signal generator, the Fourier coefficients below a chosen threshold are neglected by setting them to zero. In Section 4, a multi-input and multi-output repetitive control system is proposed together with anti-windup implementations in the presence of control signal constraints. In Section 5, an example for disturbance rejection in the presence of amplitude constraints is presented to show how a bandlimited disturbance for one input and a constant disturbance for another are reduced to insignificant values in a two input and output system. In Section 6, a robotic arm with two-degrees of freedom is used in simulation studies to show the closed-loop performance of reference tracking in a noisy environment. Section 7 concludes the paper.

2. Motivational example

This example will show that two repetitive control systems are designed using state feedback control for the same control performance. However, in the presence of control signal amplitude constraints, the commonly used repetitive control system becomes unstable when the control signal reaches its operational limits. In contrast, the proposed repetitive control system remains stable with a good performance.

A continuous-time system is given in Lee et al. (2000) with transfer-function

$$G_p(s) = \frac{0.8}{(5s+1)(3s+1)}$$

This system is sampled with a zero-order hold using the sampling interval $\Delta t = 0.25$ (s), which leads to the following state space

Please cite this article as: L. Wang, Tutorial review on repetitive control with anti-windup mechanisms, Annual Reviews in Control (2016), http://dx.doi.org/10.1016/j.arcontrol.2016.09.016