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Discrete-time anti-windup compensation for synchrotron electron beam controllers with rate constrained actuators[☆]

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ABSTRACT

By accelerating electrons to relativistic speeds, synchrotrons generate extremely intense and narrow beams of electromagnetic light that are used for academic research and commercial development across a range of scientific disciplines. In order to achieve optimum performance, the stability of the electron beam is a crucial parameter for synchrotrons and is achieved by a beam stabilisation system that is used to control the location of the electron beam and minimise any instability of the electron beam caused by external disturbances. Slew rate limits are common nonlinearities encountered with the actuators in synchrotron feedback systems which can impose significant limitations on the robustness and the performance of the control system. This paper describes an Internal Model Control (IMC) based anti-windup synthesis using an algebraic Riccati equation for a discrete-time control system to compensate against the performance deterioration in the presence of rate constraints. An Integral Quadratic Constraint (IQC) framework is used to analyse the robust stability of the anti-windup augmented closed loop system in the presence of norm-bounded uncertainty. The anti-windup augmented controller is implemented at Diamond Light Source, the UK's national synchrotron facility and improvements in robustness and performance were achieved with respect to the use of no anti-windup compensation.

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1. Introduction

Diamond Light Source is the UK's national synchrotron facility which is capable of producing light of exceptional brightness and intensity that is used in a wide range of experimental techniques to probe atomic structure. At Diamond Light Source electrons are accelerated through a linear accelerator (linac) and a booster synchrotron until they reach an energy of 3 GeV. The electrons are then injected into a circular storage ring of circumference 561 m where they circulate for several hours at constant energy. A combination of large, strong magnets deflects the electrons around the circular orbit, causing them to lose energy in the form of extremely intense and narrow beams of electromagnetic light referred to as 'synchrotron light'. Photon beamlines are placed tangentially to the storage ring to guide the narrow beams of light to experimental stations, where the light is used in a range of experiments from the design of drugs to treat viruses, to the development of non-destructive techniques in palaeontology and in the development and characterisation of novel materials for engineering applications.

In order for synchrotron light sources to produce high brilliance photon beams, the emittance (i.e. the spread of photons) must be reduced both horizontally and vertically. The vertical *electron beam* size defines the emittance of the *photon beam* and thereby to reduce the emittance of the photon beam, tight requirements are imposed on the electron beam size. Although the size and shape of the electron beam is maintained by the magnetic fields within the storage ring, the beam is subjected to disturbances from environmental effects that are coupled through the girders that support the magnets. This causes the size of the electron beam to increase and thereby increasing the emittance of the photon beam. This in turn degrades the brilliance of the photon beam used in experiments and degrades the quality of the experiments carried out on the beamlines. In order to preserve the quality of the photon beam at Diamond, a controller is used to stabilise the electron beam by controlling the beam position to within 10% of the beam

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size, which corresponds to maintaining an RMS variation of less than 12.3 μm in the horizontal plane and 0.6 μm in the vertical plane (Rowland et al., 2007).

A feedback system is used to achieved the stability required of the electron beam which uses 172 electron beam position monitors (BPMs) to detect the electron beam position around the ring in both horizontal and vertical planes and varies the current to 172 small dipole magnets (referred to corrector magnets) in each plane to change the induced magnetic field in order to correct the position of the electron beam. The control update rate is 100 μs, however the time taken to compute the control action is required to be less than 5 μs where data acquisition and processing comprises the rest of the sample time. The high dimensional and multivariable nature of the control problem, coupled with the fast computation time, requires that the structure of the problem is exploited to both reduce the multivariable nature and the computational burden. A key property of the process is that all the actuators have the same dynamics but have different steady state responses, so that the process is described by simple dynamics but a generally ill-conditioned steady state matrix. Following the approach of cross-directional control systems which generally exhibit these properties (Corscadden & Duncan, 2000; Duncan & Bryant, 1997; Featherstone, VanAntwerp, & Braatz, 2000; Heath, 1996), the steady state matrix is decomposed using orthogonal basis functions to identify and decouple the controllable modes of the system. This decomposition of the steady state response matrix allows controller dynamics for individual modes to be designed independently and simplifies tuning of the large-scale multivariable controller. For the Diamond Light Source system, an Internal Model Control (IMC) approach is used to select the controller dynamics for each mode because of the simplicity of tuning for performance and robustness since the process dynamics are inherently stable (Duncan, 2007; Gayadeen & Duncan, 2012, 2013, 2014).

Synchrotron control systems usually include slew rate limits in the power supplies for the corrector magnets to impose current limitations to protect the corrector magnets. When these limits have been reached, the rate limiter acts as a restricted tracking problem and causes performance deterioration. In this paper, an anti-windup augmentation scheme is proposed to ensure that acceptable closed-loop performance is achieved when the corrector magnet power supplies are rate limited. The main goal is to provide some augmentation to the unconstrained IMC structure to provide anti-windup compensation for the rate limited systems. Moreover, because of the highly multivariable nature of the process, difficulties arise when tuning an anti-windup compensator, so the goal is to exploit the "modal" projection used to design the unconstrained IMC controller so that the anti-windup compensators can be tuned on a mode by mode basis as well. Another consideration to the performance of the anti-windup compensators is the effect of spatial uncertainties arising from beam optics (Gayadeen & Duncan, 2012), such that any augmentation to the unconstrained controller is required to preserve as much as possible the robustness of the unsaturated closed loop to such uncertainties.

The IMC structure has been shown to possess inherent anti-windup characteristics for saturating systems (Campo & Morari, 1990; Morales, Li, & Heath, 2013; Turner, Herrmann, & Postlethwaite, 2003). However the nonlinear performance may be sluggish and therefore enhancements to the IMC structure have been suggested to improve the nonlinear closed loop performance for saturating actuators by factorising the unconstrained IMC controller to include a forward controller and a feedback term around the saturation (Goodwin, Graebe, & Levine, 1993; Zheng, Kothare, & Morari, 1993). IMC factorisations using a simple weighting on the forward and feedback term (Goodwin et al., 1993) and a more general approach (Zheng et al., 1993) were adapted for the electron beam stabilisation system under rate constraints (Gayadeen & Duncan, 2013). However the techniques are restrictive in the parameterisation of the factorisation of the unconstrained IMC controller and the design was based on intuition. Furthermore, the factorisation choices showed that the achieved constrained performance was not acceptable for synchrotron electron beam positioning control (Gayadeen & Duncan, 2013, 2014). The goal of the approach presented in this paper is to systematically parameterise the IMC anti-windup compensators on a mode by mode basis to ensure that some global performance target is met. However, the anti-windup technique developed in this paper takes a more general approach and is based on the framework introduced in Sofrony, Turner, and Postlethwaite (2010) for continuous time anti-windup synthesis for systems with rate limits using Riccati equations. In this paper, a discrete-time Riccati-based solution is proposed using a general anti-windup framework in which the anti-windup compensator is applied to the difference between the linear and nonlinear signal (Mulder, Kothare, & Morari, 2001; Turner et al., 2003; Weston & Postlethwaite, 2000). The Riccati based solution is attractive instead of an LMI-based formulation because it is more straightforward to tune, with a single parameter that captures the trade-off between performance and robustness for rate constrained actuators. Moreover an LMI-based solution would be more computationally intensive for such systems with over 1000 states and sample rates greater than 10 kHz.

For this application, the main purpose of anti-windup is to mitigate performance degradations by rate limiters. The linear controller is designed under nominal conditions and is augmented to provide anti-windup compensation. However, the robustness of the anti-windup system in the presence of plant uncertainty must be addressed. An Integral Quadratic Constraints (IQC) framework was used in Morales et al. (2013), where the robustness of the modified IMC structure for saturation constraints was compared to the standard framework in Weston and Postlethwaite (2000) and in this paper, an IQC framework is also used to develop conditions for robustness preservation of the modified IMC structure for rate constraints in the presence of norm-bounded uncertainty. However, extending an IQC approach to rate limiters is not straightforward since the discrete-time rate limiter structure is not stable in an l_2 sense and standard IQC based techniques rely on the interconnections of l_2 bounded systems. The approach taken in Gayadeen and Duncan (2013) is based on Megretski (2001) where the rate limiter is modified by including a first-order filter after the nonlinearity and a more detailed proof of the result given in Gayadeen and Duncan (2013) is presented in this paper. Furthermore, the robust stability test is used to determine how the allowable size of uncertainty is affected when the anti-windup augmentation of the constrained system is included.

The paper is organised as follows. In the following section, the process and rate limiter structure under consideration is described. In Section 3, the Riccati-based anti-windup design is developed and in Section 4, the IMC anti-windup structure for implementation is developed. In Section 5 the robust stability of the IMC anti-windup augmented closed loop in the presence of plant uncertainty is developed within an IQC framework. The IMC-based anti-windup compensators synthesised using a Riccati-based method was implemented on the booster synchrotron at Diamond Light Source. Machine data showing the performance of the implemented controller is presented and the robust stability of the structure is assessed in Section 6.

2. System under consideration

The open loop behaviour of the position of an electron beam in a synchrotron is well approximated by Duncan (2007), Gayadeen (2014)

$$y[k] = g(z^{-1})Ru[k] + h[k] \tag{1}$$

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