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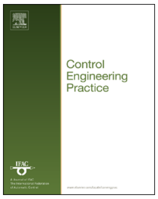

Design of an electron beam stabilisation controller for a synchrotron

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A B S T R A C T

Synchrotrons are used to generate light for academic and industry research by accelerating electrons travelling in a circular path to relativistic speeds. In order to achieve optimum performance, electron beam stability is a crucial parameter for synchrotrons. This paper describes the design of a beam stabilisation controller, using Internal Model Control. Basis functions are used to identify the controllable components of the system and it is demonstrated how by selecting dynamics for each spatial mode, enhanced performance is achieved. The robust stability of the controller in the presence of spatial uncertainties is developed within an Integral Quadratic Constraint framework using two methods of spatial decomposition: Singular Value decomposition and Fourier decomposition. The controller has been implemented at Diamond Light Source, the UK's national synchrotron science facility. Results from the controller implementation are presented and it is demonstrated how the controller design and robust stability analysis are used to tradeoff performance and robustness.

1. Introduction

In the mid 1940s, circular accelerators were built and optimised for high energy physics experiments. To maintain a circular orbit, the path of the electrons traveling at relativistic speeds was bent by a magnetic field that caused the electrons to lose energy in the form of light. In 1947, this visible light was observed for the first time at the 70 MeV synchrotron built at General Electric Co., Schenectady and is now known as synchrotron light (or radiation) (Elder, Gurewitsch, Langmuir, & Pollock, 1947; Wille, 1996). Initially, the synchrotron light produced by these machines was considered to be a nuisance. But as the potential for using synchrotron radiation as a research tool was recognised, synchrotron light experiments were performed parasitically on circular accelerators until 1980 when a dedicated synchrotron light facility was built in Daresbury, UK. Modern synchrotrons, are now dedicated light sources that use special arrays of magnets called Insertion Devices to produce even more intense and tunable beams of light. There are now over 40 synchrotrons and fourth generation light sources (i.e. lower emittance rings and free electron lasers) around the world and several facilities are currently in design or construction.

Diamond Light Source, is the UK's national synchrotron science facility, which generates synchrotron radiation for academic and industry research. To accomplish this, electrons are generated by an electron gun and accelerated to 100 MeV by a linear accelerator (linac) before being injected into a Booster synchrotron, that uses a radio-frequency (RF) voltage source to accelerate the electrons. When the electrons reach an energy of 3 GeV, they are transferred into the Storage Ring where they travel at nearly the speed of light. Fig. 1 is a schematic of the Diamond synchrotron showing the Linac, Booster and Storage Ring. The Storage Ring is made up of straight sections angled together to create a closed orbit where large bending magnets (dipoles) are used to curve the electron beam between adjacent straight sections. As the electron beam passes through the bending magnet, it emits a wide fan of synchrotron light that is channeled into a photon beamline as shown in Fig. 1, and the light is focused for use in experiments. These experiments range from rational drug design, the investigation of effects of human activities on global environments and the development of novel materials for engineering applications (Materlik, 2011).

The desired quality and properties of the photon beam used in these beamline experiments place extreme requirements on the stability of the electron beam. Although the position of the electron beam in the Storage Ring is maintained by the magnetic fields within the ring, the beam is subjected to disturbances from environmental effects that are coupled through the girders that support the magnets. There are also disturbances from the Insertion Devices that change the magnetic field as part of a beamline experiment. Movement of the photon beam centroid may either "smear out" the effective emittance, which has a deteriorating effect on the photon beam quality, or lead to an increase in measurement noise (Steinhagen, 2007). In order to minimise the effective emittance of the photon beam, a feedback control system,

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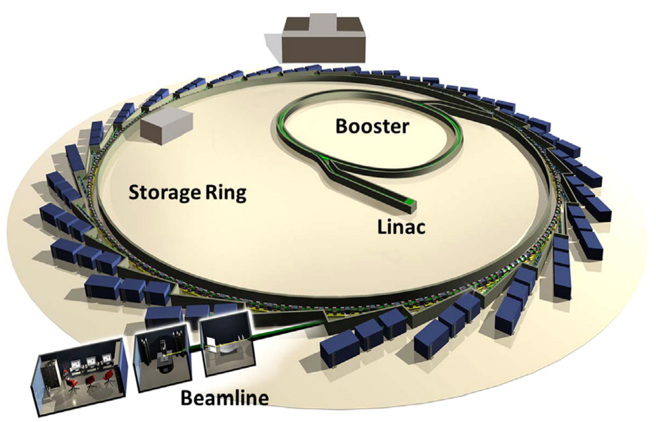

Fig. 1. Schematic of Diamond Light Source showing the linear accelerator, the booster synchrotron and the main storage ring.

referred to as Fast Orbit Feedback (FOFB) is used to control the location of the electron beam and minimise any instability of the electron beam which may propagate into the photon beam. The typical FOFB performance requirement within the industry is to reduce the resultant movement of the photon beam used in experiments by controlling the location of the electron beam to within 10% of the beam size. For the Diamond Storage Ring this requirement corresponds to the root-mean-square (RMS) variation being less than 12.3 μm in the horizontal direction and 0.6 μm in the vertical direction.

FOFB systems use beam position monitors (BPMs) to detect the electron beam position around the ring and vary the current to power supply circuits for corrector magnets which change the induced magnetic field and therefore the position of the electron beam. The Diamond Storage Ring has a total of 172 BPMs and 172 corrector magnets in each plane distributed around the 561.1 m circumference Storage Ring. Because the effect on the beam location caused by a change to the field strength of a single corrector magnet extends around the ring, there is considerable interaction between the spatial response of each of the magnets. At Diamond, the dynamic response of the corrector magnets is dominated by the first order lag in the magnet and the delay in the power electronics and it is reasonable to assume that the spatial response of the magnets is decoupled from the dynamic response. The design of the controller can then be considered to be analogous to the design of a cross-directional controller (Duncan, 1995; Duncan & Bryant, 1997; Featherstone, Van Antwerp, & Braatz, 2000; Goodwin, Carny, & Edwards, 1990; Heath, 1996; Stewart, Gorinevsky, & Dumont, 2003; Wellstead, Zarrop, & Duncan, 2000), where there is interaction between the spatial responses of the actuators that is decoupled from the dynamic response that is often modeled as a first order response plus delay.

The general approach taken for FOFB controllers is to decouple the spatial and dynamic control. For spatial control, it is common to represent the controllable components of the profile in terms of orthogonal basis functions, which is known as modal decomposition (Duncan, 1989; Duncan & Bryant, 1997; Heath, 1996). A common approach in both cross-directional control and synchrotron FOFB is to choose the singular value decomposition (SVD) to define these basis functions (Beltran & Muñoz, 2007; Hubert, Cassinari, Denard, Nadji, & Nadolski, 2009; Koch, Epaud, Plouviez, & Scheidt, 2011; Steinhagen, 2007; Terebilo & Straumann, 2006; Tian & Hua, 2011). The response matrix is typically ill-conditioned resulting from oversampling or inappropriate placement of sensors. This ill-conditioning can lead to overly large corrector settings to correct small distortions at the modes associated with less significant singular values (or high order modes). With model mismatch, the relative uncertainty is greater at high spatial frequencies and may result in closed loop instabilities (Featherstone et al., 2000). Even in the case of closed loop stability, attempting to control uncertain modes may degrade steady state performance (Heath & Wills, 2004) and it is generally accepted that the controller should not act on high order modes (Heath, 1996).

For dynamic control, the common approach for synchrotron FOFB is to use proportional-integral (PI) control (Beltran & Muñoz, 2007; Koch et al., 2011; Terebilo & Straumann, 2006; Tian & Hua, 2011). With this application, limiting the time taken for the control actions to be computed is paramount. Therefore for each mode, the same PI controller is applied but the controller bandwidth is adjusted by applying a different gain on each mode, resulting from the pseudo-inverse of the response matrix. In order to apply different dynamics to individual modes, significantly more computation is required. Considering that synchrotrons typically have more than 100 sensors and actuators respectively and like Diamond, have a controller sample rate of 10 kHz, applying different dynamics on individual modes is too computationally demanding. However, smaller systems are able to handle the extra computation, such as the Diamond Booster synchrotron which also has a controller sample rate of 10 kHz but has just 22 BPMs and correctors and can therefore apply different dynamics to individual modes. To the best of the authors' knowledge, the SPEAR3 FOFB controller is the only other machine that uses this approach (Terebilo & Straumann, 2006).

This paper presents a comprehensive approach to the controller design and in particular the tradeoff between robust stability and performance. The Internal Model Control (IMC) structure coupled with SVD for modal decomposition presented in Duncan (2007) and Napier, Gayadeen, and Duncan (2011) is maintained. In this paper it is demonstrated how the dynamics for each mode can be selected. This approach however requires significant computation, so a sub-optimal approach is also represented which reduces the computational burden. Machine data from the Diamond synchrotron is presented to compare the effect on performance of the two approaches. In this paper explicit consideration of robust stability analysis is considered in conjunction with the controller design for synchrotron electron beam stabilisation controllers. A robust stability test is applied that uses the theory of Integral Quadratic Constraints (IQCs) to obtain the upper bound on the induced l_2 gain of the closed loop system (Morales & Heath, 2011). An IQC approach is appropriate as it provides a single framework to combine different types of uncertainties and can be extended to include constraints if required (Gayadeen & Duncan, 2013). Additionally, the stability condition may be expressed as a linear matrix inequality (LMI) which is computationally attractive for this large dimensional problem. The robust stability test is presented for the system where SVD is used to decompose the response matrix. Using SVD to define basis functions can be considered as shifting the control problem into a different space, however the physical interpretation of the analysis in the transformed space is not always clear (Duncan & Bryant, 1997). Alternatively, the use of Fourier transforms can be used to determine the spatially controllable subspace of the response matrix (Duncan, 1989; Stewart, 2000; Stewart et al., 2003) which, when analysing the orbit of the electron beam, maintains a direct physical interpretation. In Gayadeen and Duncan (2012) it was shown that a Fourier decomposition of the response matrix can lead to a realistic representation of the uncertainty where the uncertainty descriptions associated with the actuators, sensors and process can be decoupled. In this paper a comparison with SVD for robust stability is presented and the application of both the SVD and Fourier methods for robust stability analysis is demonstrated. Machine data from both the Storage Ring and Booster is presented and it is demonstrated how the results are