DIAMOND LIGHT SOURCE ELECTRON BEAM POSITION FEEDBACK: DESIGN, REALIZATION AND PERFORMANCE

M. T. Heron, M. G. Abbott, J. A. Dobbing, G. Rehm, J. Rowland, I. S. Uzun, Diamond Light Source, Oxfordshire, U.K. S. Duncan, University of Oxford, Oxfordshire, U.K

Abstract

The electron beam in the Diamond Synchrotron Light Source is stabilised in two planes using the Fast Orbit Feedback system. This feedback system takes the beam position from 168 Libera electron beam position monitors for each plane, and calculates offsets to 336 corrector power supplies at a sample rate of ~10 kHz. The design and realization of this system, together with its performance and operational experience will be presented.

INTRODUCTION

Diamond, a third generation 3GeV synchrotron light source [1], commenced operation in January 2007. The storage ring (SR) is based on a 24-cell double bend achromatic lattice of 561m circumference. The photon output is optimised for high brightness from undulators and high flux from multi-pole wigglers. The current operational state includes twelve photon beamlines, with a further nine beamlines now under design or construction.

To achieve the required photon beam stability, the electron beam needs to be maintained to a stability better than 10% of the beam dimensions in X and Y. Despite considerable effort to decouple the electron beam from environmental disturbances, a range of disturbances are still coupled into the beam. These come from a broad range of sources, which include environmental noise from water and air conditioning pumps, effects of operating Insertion Devices in the Storage Ring and thermally induced effects. To suppress these, a Fast Orbit Feedback System (FOFB) performs global orbit correction, using the electron beam positions from 168 horizontal and 168 vertical electron Beam Position Monitors (eBPMs) to control 168 horizontal and 168 vertical corrector magnets [2,3].

REALISATION

To realise the required data transfer (eBPM to Computation nodes) at a 10 kHz update rate, a custom communication controller, implemented in VHDL, is used to move horizontal and vertical positional and control data from the 168 Libera eBPMs to each of 24 computation nodes [4]. This network uses the multi-gigabit serial transceivers on the FPGAs in the Libera eBPMs and PMC interface cards on the computation nodes. The network topology is structured as a 2D torus, with one computation node per Storage Ring cell, and gives a degree of resilience to failure of single or combinations of eBPMs or links. The structure is shown in Fig 1. The communication controller utilises a data-forwarding protocol whereby each node forwards its own data, plus each piece of incoming data once. The data is encapsulated in a low-overhead packet including CRC. Each of the computation nodes receives the data from all eBPMs, and uses a dedicated MVME5500 VME processor board to calculate the outputs for a sub pseudo-inverse response matrix corresponding to the seven correctors for that cell. The regulators are then implemented as eighth order IIR filters on the outputs of the sub pseudo-inverse response matrix followed by a series of boundary checks to trap for erroneous conditions and to shut down the system in a graceful way in the event of unrealistic corrector demands. The new PSU demand values are written via dedicated 1Mbps point-to-point links from each computation node to the fourteen PSU controllers for that cell.

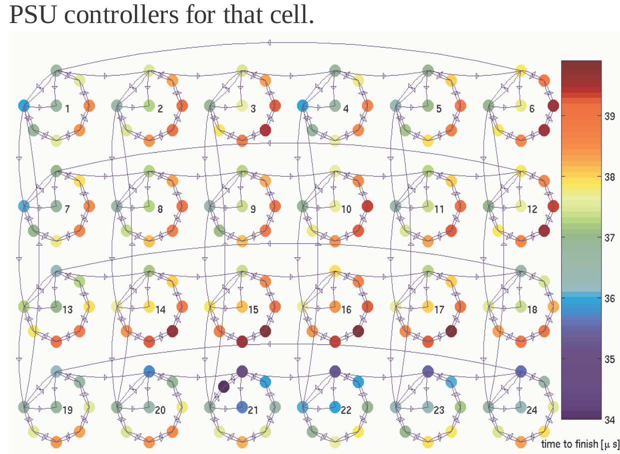

Figure 1: Communication network topology, with each circle being one cell consisting of seven eBPMs, and a computation node in the centre. The interconnection is as a 2D torus showing propagation delay between 34 μsec and 40 μsec.

CONTROLLER

The feedback controller calculates the new corrector values from the beam position errors measured by the eBPMs. This calculation is based on mapping the errors from monitor space (eBPMs) into corrector space and then applying regulators with same dynamics to calculate the updated values to be written to the corrector PSUs.

The DC mapping from Corrector space to Monitor (eBPMs) space is defined by the Response Matrix (RM) of the Storage Ring and is dependent upon the optics of the Storage Ring. This can be measured from the Storage Ring or determined from the model of the Storage Ring. For the feedback process the mapping from Monitor

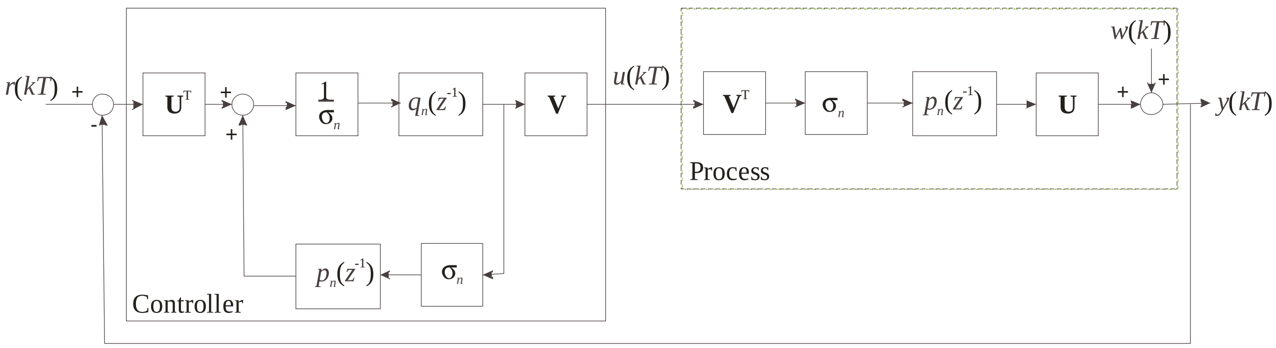

Figure 2: Feedback controller structure, r demanded orbit, u correctors, y measure orbit, p plant, q compensator for plant, σ singular values.

(eBPM) space to Corrector space is required, which is the inverse of the RM. This may be derived by a number of approaches, one of which is Singular Value Decomposition (SVD). SVD is used to break down the RM into its Input Modes (U), Output Modes (V Transposed) and a diagonal matrix (Σ) of the Singular Values (σ). A pseudo inverse response matrix can then be produced from the transposed Input Modes, Output Modes and inverted non zero Singular Values in (Σ). However, in this application the Singular Values are ill-conditioned, covering three decades; this would make the system sensitive to small changes (noise) in the eBPMs. To address this Tikhonov regularisation [5] is applied to scale the singular values, thereby retaining information for all modes. Using the scaled singular values a pseudo inverse response matrix is created. For the implementation, this is then partitioned into 24 sub matrices with dimension 7x168, for each of the computation nodes, with each giving the outputs for 7 PSUs.

With the same dynamics on each output, the system can be analysed as a SISO system whereby the transfer function of the process is determined by first order lag in the power supply and magnet and by latency from the filters in the Libera eBPMs and the data transfer. This then approximates to a low pass filter plus a delay of six sample periods. An Internal Model Controller (IMC) is used to realise the controller. This uses a model of the process p(z) in the feedback part of the loop, together with compensation for the process in the forward loop, and provides a single tuning parameter controlling the bandwidth of the loop, Fig 2.

IMCs with the same dynamics operate on each output of the pseudo inverse response matrix [6]. This approach minimises the computation required, as the controller only has to be applied for the outputs required by that computation node, i.e. the PSUs in that cell, and so lends itself to being distributed. A secondary loop performs correction of the residual horizontal orbit by adjusting the RF frequency.

PERFORMANCE

The FOFB provides around 20 dB of suppression at 16 and 24 Hz where most ground noise is coupled to the girders, with a crossover point at 80 Hz. This is in good agreement with the model, Fig 3, and meets performance targets. The FOFB is unable to correct beam motion near 300 Hz caused by the girder cooling water flow and mechanical resonances, Fig 4.

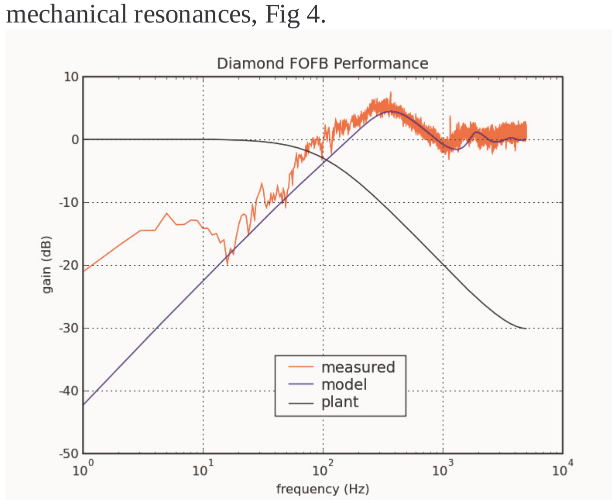

Figure 3: Theoretical and measured suppression in the vertical plane. Below 10 Hz is noise dominated in the measured data.

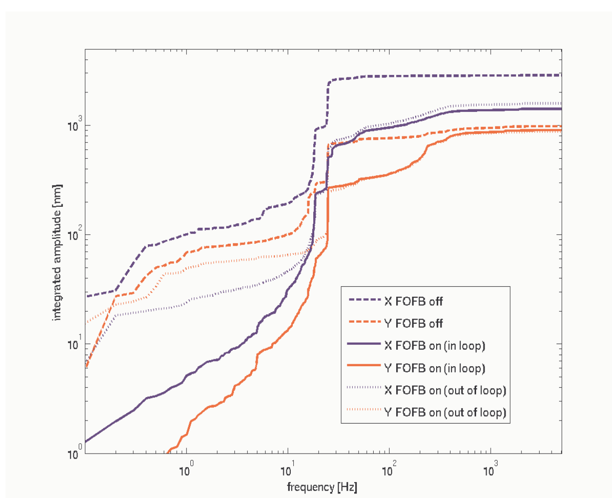

Figure 4: Integrated amplitude of positional noise for Feedback Off, Feedback On, in loop, and Feedback On, out of loop.

The FOFB also prevents insertion device movements from affecting other beam users by compensating for the beam motion remaining despite the use of feed-forward tables.

OPERATIONAL EXPERIENCE

The operational experience of the FOFB system has been very good; however as with any system that can dump the stored electron beam under a fault condition, minor or intermittent problems have a serious impact on the overall reliability of the storage ring. The following operational problems have been encountered:-

- To maintain loop stability, the FOFB is only operated in the linear region of the eBPMs, up to 100 μm. Inputs outside this limit stop the system. Large glitches driven by the eBPM analogue front-ends were regularly stopping the system; whilst the worst few eBPMs were replaced, this only reduced the frequency of glitches across the whole system to once per week. The controller logic was developed to saturate and ignore any one out-of-limits input, thereby alleviating the problem.
- The instantaneous demand values produced during feedback produce a poor steady-state orbit as the controller proportional gain is greater than one. To compensate for this, when feedback stops, a set of suitably-filtered steady-state values is written; this greatly improves the resultant open-loop orbit and reduces the disruption caused by any unexpected stops of the Feedback process.
- During long runs, corrector strengths were increasing near disabled eBPMs due to the growth of unobservable modes. These were damped by moving the integrator pole in the controller slightly toward the origin.
- An intermittent hardware fault on one computation node (VME crate) caused the DMA transfer of the BPM data into processor memory to fail. This prevented that node from writing updated values to the corrector magnets or from shutting down the system. This resulted in growth of the orbit error and eventually the beam dumped. This condition was trapped and used to shut down the feedback process.
- The FOFB will stop whenever the number of nodes on the feedback network changes. One particular eBPM failure mode prevented the FOFB system from starting. If the eBPM processor crashed, the feedback communications controller could become desynchronized and the number of nodes on the feedback network would oscillate. This has been fixed by communicating the identities of each node as well as the total number so that unresponsive eBPMs can be ignored. This fault occurred roughly every two weeks and was disruptive because the eBPMs form part of the machine protection system and cannot be rebooted without dropping the beam.
- Loss of synchronisation from a primary eBPM, due to the clock daemon failing, highlighted a bug in the Communication Controller whereby data was corrupted. This was due to improper resetting of receiver FIFOs on the computation node Communication Controller PMC modules when-out of-frame data arrived. During normal operation the problem was not apparent as all Libera eBPMs are synchronised and data arrives within the correct frame.

The automatically-archived post-mortem facility saves the last one second of internal state from all feedback processors through the EPICS based control system whenever the FOFB stops, and was essential to the diagnosis of these problems.

As a consequence of limited access to the Diamond Storage Ring for development and analysis it has been difficult to develop the FOFB. As a result, a programme of work to implement the same architecture of FOFB on the Diamond Booster synchrotron is now planned. This will be used as a test bed for future development and analysis before migrating the development on to the Storage Ring.

CONCLUSION

The Diamond FOFB system is operating successfully and achieving the required level of suppression of beam disturbances. It is recognized that the requirements will become more demanding in the future; hence work is planned for ongoing analysis to improve the performance of the feedback system.

REFERENCES

[1] R.P. Walker, “Commissioning and Status of the Diamond Storage Ring”, APAC 2007, Indore, India
[2] S R. Duncan, “The Design of a Fast Orbit Beam Stabilisation System for the Diamond Synchrotron”, University of Oxford Department of Engineering Science Technical Report, 2007.
[3] J. Rowland, M. G. Abbott, J. A. Dobbing, M. T. Heron, I. Martin, G. Rehm, I. Uzun, S. R. Duncan, “Status of the Diamond Fast Orbit Feedback System”, Proceedings of ICALEPCS 2007
[4] S. Uzun, R. Bartolini, G. Rehm, J.A. Dobbing, M. T. Heron, J. Rowland, “Initial Design of the Fast Orbit Feedback System for Diamond Light Source”, Proceedings of ICALEPCS 2005.
[5] A. Neumaier, “Solving Ill-Conditioned and Singular Linear Systems: A Tutorial on Regularization”, SIAM Review, 40, 636-666, 1998
[6] W. P. Heath, A. G. Wills, “Design of Cross-Directional Controllers with Optimal Steady State Performance”, European Journal of Control, 2004.