FAST GLOBAL ORBIT FEEDBACK SYSTEM IN SPEAR3*

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Abstract

The new fast orbit feedback system (FOFB) is being commissioned at the SPEAR3 light source. The system has a 4kHz sampling rate and 100Hz bandwidth. The correction algorithm is based on the Singular Value Decomposition (SVD) of the orbit response matrix. For performance tuning and additional flexibility when adding or removing Corrector Magnets (CM) and Beam Position Monitors (BPMs), we implement an independent control loop for each orbit eigenvector used. This paper discusses design and performance of the system.

INTRODUCTION

SPEAR3 [1] is a 3rd generation light source. The orbit must be kept stable to within a few percent of the electron beam size. Sub-micron stability in a 100 Hz bandwidth is desirable and has been achieved in similar machines.

Since the start of operations in 2004, SPEAR3 relied on a slow orbit feedback (SOFB) that corrected the orbit every 5 seconds. In addition, to compensate for the user controlled Insertion Device (ID) movements, we implemented a feed-forward compensation scheme running at 10Hz, using four CMs adjacent to the IDs.

The new fast feedback (FOFB) replaces the SOFB. One of the requirements is that it be a sole orbit feedback system in the DC to 100Hz bandwidth using all available BPMs and CMs. It should correct orbit error caused by weak uncorrelated 'background' vibrations of magnets and supports as well as strong localized disturbances, such as undulator gap changes.

SYSTEM DESIGN

The main purpose of the transverse orbit feedback system is the reduction of beam motion due to mechanical vibrations which are dominant below 100Hz. The limiting factors to the achievable open-loop bandwidth are CM field penetration into the vacuum chamber (copper with CuNi inlays for enhanced bandwidth to ~100Hz), CM power supply bandwidth (~700Hz) and aliasing of the multiplexed beam position monitors [2]. A discrete-time ('digital') controller closing the feedback loop inevitably introduces a finite time delay ('dead-time') which must be kept short enough so that the reduction of phase margin remains acceptable [3].

Hardware

We believe that computational and timing requirements can be met with modern general-purpose computer and networking technology, and that special signal processors and proprietary communication links casn be avoided. Using standard technology reduces risks (single-source dependency), cost and eases maintenance, portability and upgrades.

Software

In order to meet our stringent timing requirements, we use a hard real-time operating system (RTEMS) which guarantees timely scheduling of interrupts and critical tasks while, at the same time hosting the standard software interface (EPICS) to the SPEAR3 control system for controls and monitoring.

Architecture

FOFB (Figure 1) is a distributed system comprised of 2 BPM processors (each acquiring up to 56 [currently 27] BPMs), one feedback controller, 14 corrector power supply processors (each driving 8 analog supplies), a number of dedicated point-to-point network links, a standard LAN, and a timing system which provides global synchronization.

Timing

A 4kHz clock signal with embedded timestamp and event/trigger information is available to all components in the system and synchronously drives the BPM data acquisition, the feedback processor and the power supply controllers.

Triggers and timestamps are available to all FOFB components. They are a powerful tool for synchronization of diagnostic data acquisition and correlation of data sets at a 250us resolution. For example, the open loop response of the system can be measured by triggering a current step in a number of correctors and synchronously reading the BPM response, thus yielding complete phase information.

Communications

All components of the orbit feedback are connected to the ordinary control system LAN. This connection is used by the EPICS IOC software to communicate 'ordinary' parameters, monitors and setpoints etc. to the control system.

All processors participating in the feedback are equipped with additional Fast Ethernet ports. A special, low-level Ethernet packet driver (circumventing TCP/IP) pipes 4kHz data into unidirectional, dedicated point-to-point links thus avoiding collisions and other non-deterministic features of TCP/IP. Two such links are used for streaming orbit readings from the BPMs into the feedback processor which in turn broadcasts new setpoints on a similar connection to all power supply processors at once. This solution is inexpensive, fast and reliable.

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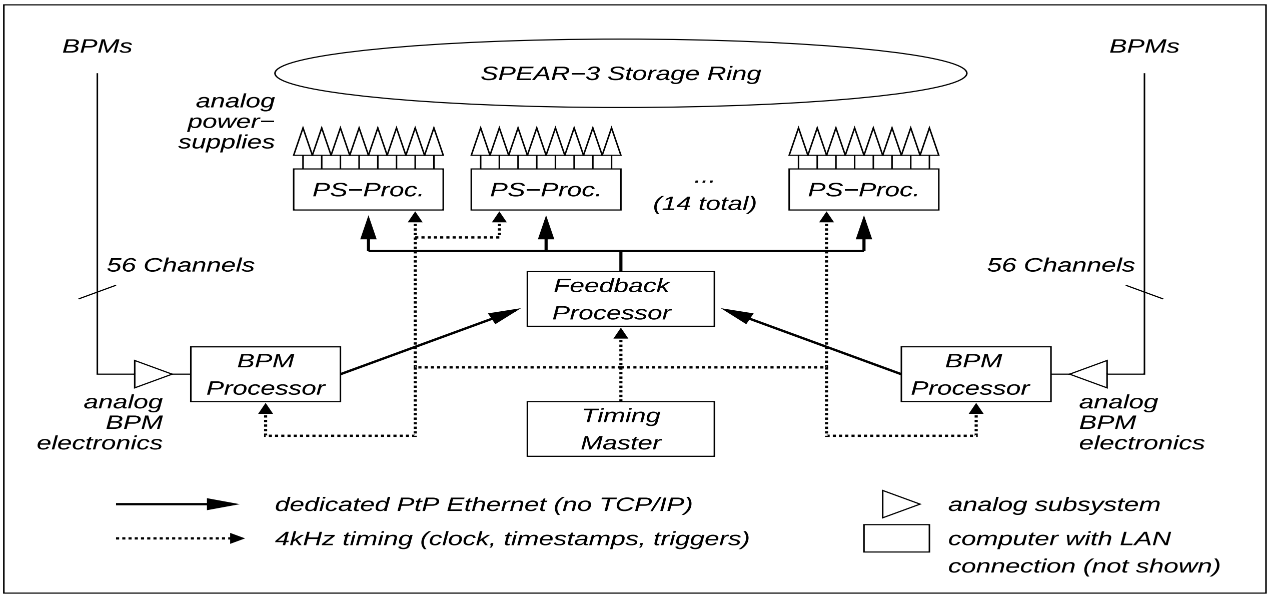

Figure 1: SPEAR3 fast orbit feedback system architecture

BPM Processors

The BPM processors acquire readings from the BPM electronics, perform position calculations, and stream the orbit data to the feedback processor at 4kHz.

Several history buffers are available for capturing timestamped 4kHz data using global triggers. Thus, synchronous orbit readings at 4kHz are available for many diagnostic purposes.

Furthermore, the BPM processors provide averaged position readings as well as an interface between the fast data acquisition and the control system so that their information is readily available at the operator consoles.

Power Supply Processors

These processors read setpoint information from the dedicated 4kHz network and update the DACs driving the CM power supplies. A wide range of additional features (e.g., 4kHz waveform tables) are available from the control system.

Feedback Processor

The central feedback processor obtains positions from the BPM processors every 250us. The correction algorithm is based on an SVD [4] of the orbit response matrix:

$$\Delta\bar{x} = R\Delta\bar{\theta} \qquad R = USV^T$$
$$\Delta\bar{\theta} = VS^{(-1)}U^T\Delta\bar{x} \tag{1}$$

where Δx is the orbit error. U and V are matrices whose columns form an orthogonal basis in BPM (Δx) and CM (Δ*θ*) space. S is the diagonal matrix of singular values. $S^{(-1)}$ is its pseudo-inverse with numerically large values on the diagonal replaced with zeros.

The feedback processor multiplies the deviation from the desired orbit error (Δx) by $S^{(-1)}U^T$ and projects it into the diagonalized 'pseudo-eigen' space. The Proportional-Integrator (PI) control algorithm operates in this diagonal space and the relevant parameters can be adjusted for each mode separately.

Thus, modes with small associated singular values can be assigned a reduced bandwidth so that noise does not translate into large random 'corrections'.

Setting PI coefficients differently for different eigenmodes is justified by the nature of orbit errors. Errors from 'legitimate' perturbations (vibration of magnets) are aligned more with the eigenvectors with large singular values unlike random noise, that projects uniformly. Figure 2 shows the frequency spectrum of the measured orbit error in the eigenvector space $\Delta\bar{x}_u = U^{(T)}\Delta\bar{x}$

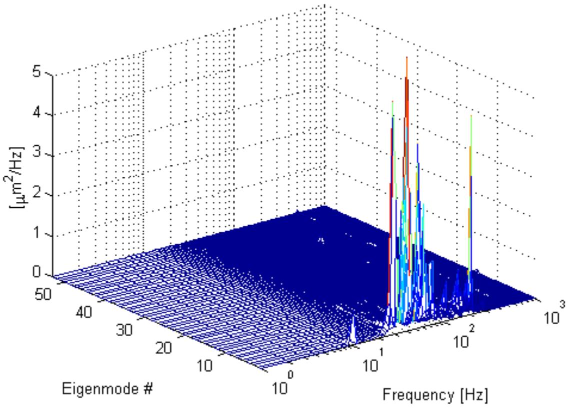

Figure 2: Orbit error spectrum in eigenvector space.

This scheme inherently avoids problems with uncontrollable or unobservable parts of the system since an excessive number of internal states ('integrators') of the correction algorithm would inevitably cause uncontrollable or unobservable modes to build up in the corrector current pattern, eventually leading to large overcurrents. We do not try to correct modes with too small singular values as much or as fast as other modes.

The most computationally expensive operation is a multiplication of a matrix (~100x200) by a vector (~200x1) to be carried out every 250us.

The corrections are then broadcast to the power supply processors where they are multiplied by corresponding rows of the V matrix (in order to transform the eigen-modes into drive currents). This is done in a distributed manner - each processor only has to work on 8 rows.

The entire processing (BPM reading to correction algorithm to driving power supplies) currently takes about 750us (3 clock cycles) but we expect to reduce this to 500us by upgrading the BPM processors with faster CPUs.

OPERATIONAL PERFORMANCE

Fast orbit feedback has been in operations since June, 2006. Integrator loop gains were set conservatively for the start of operations. Studies to find optimal tuning are underway.

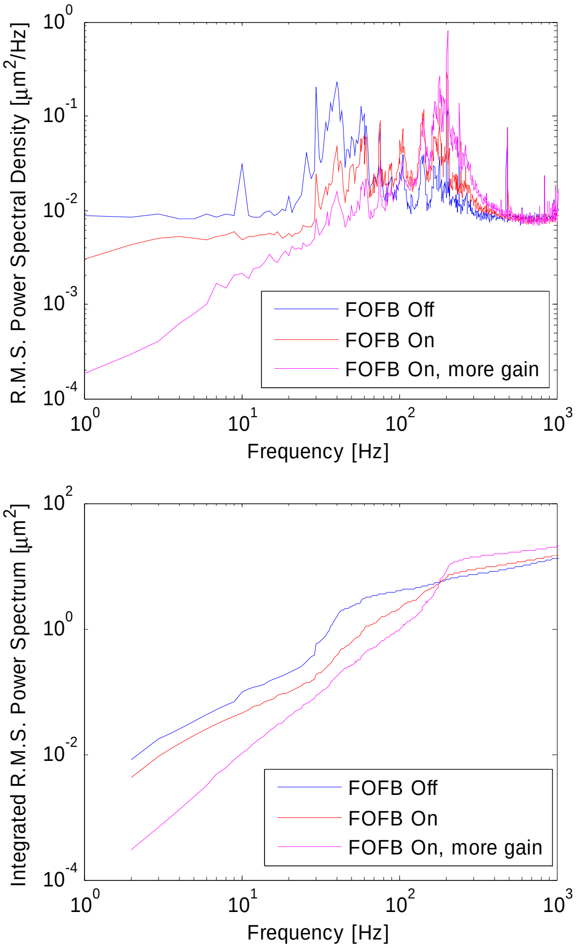

Figure 3: Orbit error (spacial r.m.s.) power spectrum and power spectral density

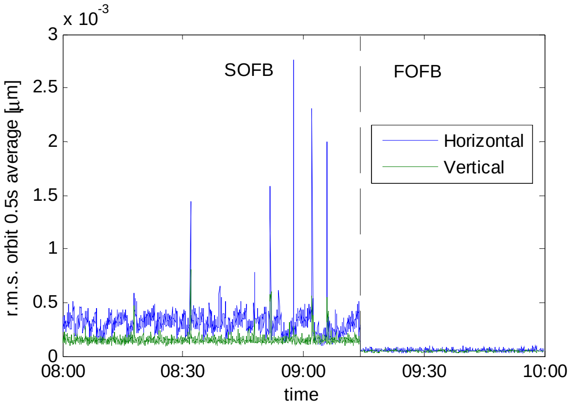

Figure 4: Suppression of orbit errors due to undulator gap changes and other localized disturbances.

Distributed orbit perturbations, wide bandwidth

Figure 3 shows the effect of the fast feedback in reducing wideband global orbit motion, such as the one illustrated in Figure 2.

Local perturbation, low bandwidth

Synchrotron radiation users independently control IDs. Gap or phase changes in undulators occur on a 1s time scale. Local feed-forward correction was implemented using ID trim coils. Nevertheless, without FOFB, these changes cause global orbit distortions of a few μm r.m.s.

Another SPEAR-specific source of motion was identified as vehicle traffic on the overpass bridge into the storage ring that causes slow (~1s) motion of the floor.

The effect of both types has been effectively suppressed by FOFB (Figure 4).

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