DIGITAL ORBIT FEEDBACK COMPENSATION FOR SPEAR*

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Abstract

The global orbit feedback system for SPEAR will be upgraded in 1995 to achieve 30-50Hz closed loop bandwidth. In this paper, we discuss issues related to measurements of the corrector frequency response, the DC response matrix, digital compensator design, and the impact of sequential bpm sampling. Results from detailed simulations are included.

1. INTRODUCTION

SPEAR is a 234m synchrotron light source that was originally designed for e^-- e^+ collider physics. Because of this history, many features built into 3rd generation light sources are not available in SPEAR. The bpms, for instance, were installed before the modern notions of accelerator impedance were developed, and their geometry was not optimized for high resolution measurements. In addition, many of the magnets are subject to thermal fluctuations, hysteresis, and to ground motion propagating through girder supports. These vibrations lead to electron beam motion in the 1-20Hz range, and diurnal drift of the orbit.

At present, 3-magnet bumps are used in analog servo loops to stabilize each photon beam position at a monitor located 5m to 15m from the source point[1]. If we also control the electron beam position at the source point, we effectively control the angle of the photon beam. So far, we have stabilized diurnal motion of the electron beam by correcting the orbit with a feedback system operating at ~1min intervals. The next step is to speed up the orbit acquisition in order to control beam motion at several Hz and above. As at other laboratories, the SPEAR system uses either harmonic or eigenvector orbit correction[2-4] and a 'bump subtraction' algorithm to decouple the global system from the analog servo loops at each photon beamline.

Commissioning the global feedback system exposed some interesting issues peculiar to SPEAR. Many of the vertical corrector magnets, for instance, are located on QF magnets (low β_y), are not optimally located for orbit control, and have only a limited actuator range. In addition, it was found that the bpm readback values depended on the total beam current and the bunch pattern.

Most of these problems have been overcome by a combination of careful machine handling, empirical selection of the eigenvalue cut-off point, and filtering data in the feedback code. As a result, we now have a system that can stabilize the electron beam orbit to ±100 microns (peak) over a 24hr period. In addition, the corrector currents used in the 3-bump servo loops are 5 to 10 times less than without the global feedback.

Later this year, we will introduce a fast bpm processor to reduce the orbit feedback cycle time to ~1ms and include the photon beam bpms in the digital control algorithm. In this configuration, we can readily apply a different relative weight on each bpm to adjust for measurement noise, and/or weight each corrector magnet to control the use of individual actuators. The fast feedback system will use a dedicated DSP board in a VME crate to process the orbit information. (See ref. [5] and companion paper [6]) The goal is to stabilize motion at both the electron and photon bpms with a 30-50Hz closed-loop bandwidth.

In this paper, we will discuss our present approach to compensation of the frequency dependent components of the MIMO (multi-input, multi-output) feedback system. Following the outline of a simple compensator design, we will discuss more challenging aspects of the SPEAR feedback system. The main difficulties are (1) compensation for corrector magnets with different frequency response, (2) delays incurred from sequential bpm sampling, and (3) differences between the measured response matrix and the actual machine response.

2. SYSTEM RESPONSE

Frequency response is presently measured by driving corrector power supplies with a sinusoid (or random) waveform generator and measuring the output at a broadband photon beam position monitor. When the new bpm processor and DSP system come on line, transfer functions between all correctors and bpms will be evaluated across the complete open loop system.

We expect the transfer functions are dominated by power supply response, eddy currents in the magnet cores, and field penetration into the vacuum chamber. A typical frequency response from one of the 26 vertical correctors wound on a solid core quadrupole is plotted in Fig 1. In this case, a two-pole fit of the Bode plot is indicated. Fits to independent measurements produced close agreement for the low frequency pole (~25Hz) and about 30% difference at the high frequency pole (~250Hz). Since the two pole model only approximates the exact characteristics of the hardware, the final optimization of the compensator design will be the result of empirical tuning. Points above about 300Hz are not indicated in these plots because the phase becomes a non-linear function of drive amplitude.

The DC response to each corrector as measured at each electron and each photon beam bpm forms the response matrix for the feedback algorithm. It is also possible to include the rf frequency in the response matrix to correct DC orbit shifts. The main feedback algorithm consists of first projecting orbit perturbations onto a subset of theeigenvectors from the inverse response matrix (SVD pseudo-inverse) to produce a set of corrector control signals.

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*work supported in part by Department of Energy Contract DE-AC03-76SF00515 and Office of Basic Energy Sciences, Division of Chemical Sciences.

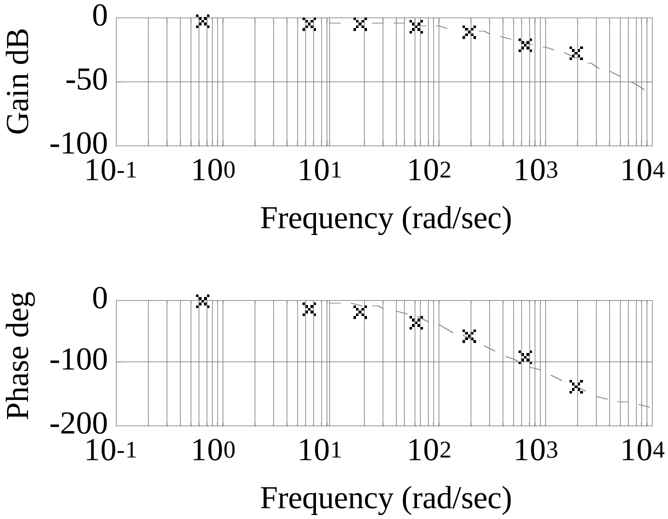

Figure 1 Two-pole fit to measured frequency response of a vertical corrector magnet in SPEAR.

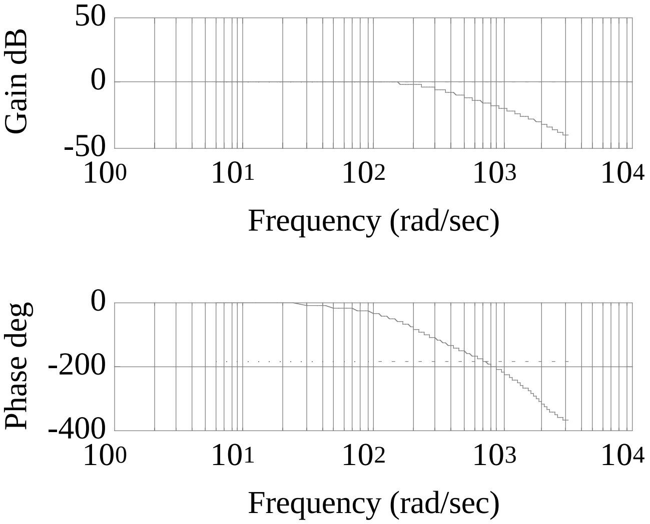

Figure 2 Closed-loop Bode plot with PI compensated corrector magnet.

The resulting control signals are then digitally compensated to achieve the desired closed-loop frequency response. Details of the eigenvector cut-off calculation can be found in reference [7].

3. DIGITAL COMPENSATION

Based on the above measurements, a digitally compensated closed-loop Bode plot for a 1kHz sample rate is shown in Fig. 2. For this plot, we included a 1ms computation delay (single cycle) in the open loop transfer function. As discussed in Section 5, there will also be a range of bpm readback delays in the orbit acquisition system. The simple compensator shown here uses a single integrator pole and a single real-axis zero (PI-control) to achieve a closed loop bandwidth of about 25Hz. To avoid excessive actuator drive current, derivative control was not used in this example. A PI compensator simplifies the design and the system behavior while we gain operational experience. A state-space feedback system with optimal gain coefficients will be pursued if simulations show it to provide operational benefits.

In SPEAR, four additional correctors, previously used near the interaction points for collider experiments, exhibit a more broad band frequency response. For reasons discussed in more detail below, we will try to equalize the frequency response of all correctors. In short, equalization filters permit factoring a single frequency-dependent term from the response matrix, and simplify development of the feedback system.

4. DIGITAL FEEDBACK SIMULATOR

A computer simulation program was written by one of the authors (Keeley) to evaluate aspects of the feedback behavior that cannot be characterized analytically. The main features of the simulator are direct integration (Bulirsch-Stoer) of the differential equations representing the analog parts of the system, and difference equations representing the digital parts of the system. The analog part models the time dependence of the system response beginning from the discrete inputs to the corrector power supplies, through the corrector magnets, and finally the field penetration into the vacuum chamber. The numerical coefficients for the differential equations are determined from frequency response measurements. We chose to use a differential equation model to permit sampling of the orbit at arbitrary times.

In the simulator, the actuator drive currents are modeled as piecewise constant outputs from the DACs as driven by the digital computer. The orbit is obtained by 'sampling' the ongoing solution of the differential equations for the fields in the vacuum chamber, and using the DC orbit response matrix to compute beam position. The bpm readings are related to the physical orbit through another set of equations representing the transfer function of the bpms and the bpm processor hardware. This component of the transfer function will be measured directly when the fast bpm processor becomes available.

The digital part of the simulator includes the bpm sampler, the orbit correction calculation, and the digital frequency compensation stage. It is anticipated that the DSP calculation (including voltage to position calculation, matrix multiply, digital filters and I/O) will be less than 1ms.

In general, the response matrix used to calculate the orbit correction need not be the same as the matrix used to simulate the response of the machine to corrector inputs. This feature allows simulation of imperfect response matrix measurements, or systematic changes in the lattice (see section 6).

5. SEQUENTIAL ORBIT SAMPLES

The vertical orbit feedback system on SPEAR will use about 30 electron beam and 10 photon beam position monitors. It is anticipated that the new bpm processor will sample the bpms sequentially around the ring, with a dwell time of about 10μs (~10 turns) at each button. The time interval for a complete orbit acquisition will be on the order of 1ms, which is close to the desired feedback cycle time.

Note, however, that although the most recent bpm reading will havc a delay of ~40μs, the initial reading will have about 1ms delay.

In practice, the different bpm sample delays produce different open loop transfer functions. Since each corrector drives every bpm in the global feedback system, even an individual compensator for each corrector cannot account for a different sample delay of each bpm. In effect, the closed loop system becomes fully coupled. The coupling implies that if a step is applied to a single bpm readback, the orbit will initially move at *all* the bpms. Simulations of SPEAR show that although the system is typically stable, the transients caused by coupling can be large.

One simple solution is to equalize all the corrector transfer functions, and then design a single compensator that gives a satisfactory step response for the first and the last bpm in the sample sequence. An example of this approach yields the step responses for the first and last bpm as shown in Fig. 3. The corresponding Bode plot for the last bpm sample (one cycle delay only) was shown in Fig. 2.

An alternative approach which is possible with equalized transfer functions is to design a set of 'closed bump' corrector patterns to control each individual bpm. For each corrector pattern, a different frequency compensation can be used to account for the different delay at the particular bpm.

6. RESPONSE MATRIX ERRORS

Simulations have been made to assess problems associated with a response matrix measurement which is an imperfect representation of the machine.[†] BPM noise, corrector hysteresis, or thermal effects for instance, can all lead to a mismatch between the machine response and the measured response matrix.

The feedback simulator has been run using two independent measurements of the response matrix on SPEAR. One matrix is used to simulate the machine response to corrector inputs, and the other (really its pseudo-inverse) is used in the feedback controller. The system is often found to be unstable when the complete set of SVD eigenvectors is used in the control calculations. This is true even when all correctors are assumed to have the same frequency response (or even an 'instantaneous' response, with only a single integrator for DC regulation). The system can be stabilized by using only the dominant 14 or 15 SVD eigenvectors. Interestingly, this number of eigenvectors is roughly the same number of eigenvectors required to correct the orbit to the noise floor[7].

So far, we have not discovered an analytical way to predict the eigenvector cut-off number for which the system will be stable. Based on optics arguments, however, we found the problem can be eliminated in SPEAR by excluding the 4 bpms nearest to the (former) collider points in the lattice. We suspect that since the bpms and the nearby correctors are separated by ~180° phase advance, the feedback is sensitive to response matrix errors in this region.

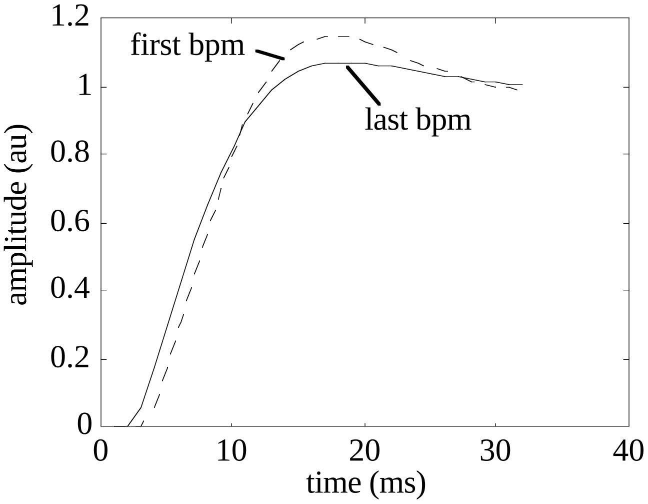

Figure 3 Closed loop step response for first and last bpm in sampling sequence.

If the matrix used in the calculations is exactly the same as the matrix used to simulate the machine, the simulations are always stable, independent of the eigenvector cut-off point.

7. DISCUSSION

In the next development phase with fast data acquisition and fast data processing, the issues of equalizing the correctors and finding a common frequency compensation for the closed loop system will be critical. The operating parameters used in the digital compensation satge will be refined empirically using the on-line system to seek optimum conditions. In particular, the relative weighting for bpms associated with each photon beamline will be adjusted to satisfy user needs. The eigenvalue cut-off value will be adjusted according to results from simulations and experimental observations. Adaptive methods to update the response matrix values used in the controller will be explored.

8. ACKNOWLEDGMENTS

The authors would like to thank Max Cornacchia for encouraging this work. We would also like to thank Ivan Linscott and Jim Sebek for many useful discussions.

9. REFERENCES

[1] R. O. Hettel , Trans. Nuc. Sci. **NS-30** 2228 (1983).
[2] L. H. Yu, et al, NIM **A284** 268 (1989).
[3] A. Friedmann and E. Bozoki, Proc. of Orbit Correction and Analysis Workshop (Brookhaven National. Laboratory, 1993
[4] Y. Chung, G. Decker and K. Evans, Jr., Proc. 1993 IEEE PAC, Washington D.C., 1993.
[5] R. Hettel, et al, Proc. 4th European PAC, London, England, June 27-July 1, 1994.
[6] R. Hettel, et al, these proceedings.
[7] J. Corbett, D. Keeley, R. Hettel, et al, Proc. 4th European PAC, London, England, June 27-July 1, 1994.

[†] This condition is different from simulations with numerically 'exact' response matrices that use a reduced number of eigenvectors because now the model and machine eigenvectors are different.