SIMULATION OF THE APS STORAGE RING ORBIT REAL-TIME FEEDBACK SYSTEM UPGRADE USING MATLAB*

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Abstract

The Advanced Photon Source (APS) storage ring orbit real-time feedback (RTFB) system plays an important role in stabilizing the orbit of the stored beam. An upgrade is planned that will improve beam stability by increasing the correction bandwidth to 200 Hz or higher. To achieve this, the number of available steering correctors and beam position monitors (BPMs) will be increased, and the sample rate will be increased by an order of magnitude. An additional benefit will be the replacement of aging components. Simulations have been performed to quantify the effects of different system configurations on performance.

INTRODUCTION

The APS Upgrade project will upgrade the APS to higher beam current, which requires stricter beam position stability. The upgrade of the APS storage ring real-time feedback (RTFB) system is the key project to reach this goal. The present APS real-time feedback system is limited to use 38 high-bandwidth fast steering correctors and about 160 beam position monitors in each plane. It operates at 1534.176-Hz sampling rate.

The system closed-loop bandwidth is about 60 Hz. The proposed upgrade will extend the correction bandwidth to 200 Hz [1]. To achieve this 200-Hz closed-loop bandwidth, an increase of sample rate to the range of 10 kHz to 20 kHz is required. The proposed real-time feedback system double-sector architecture is shown in Figure 1.

The upgraded system will double the number of BPMs and correctors used. The present system uses some components, for example, DSPs that are quite out of date and have very limited computation capability. The new system will use field programmable gate arrays (FPGAs) to solve the computation bottleneck. The existing system uses a reflective memory network to interconnect the feedback system nodes. These reflective memory modules are also obsolete and will be replaced by a high-speed transceiver and communication controller implemented in FPGA.

The MATLAB tools were used to simulate the upgraded real-time feedback system in this paper.

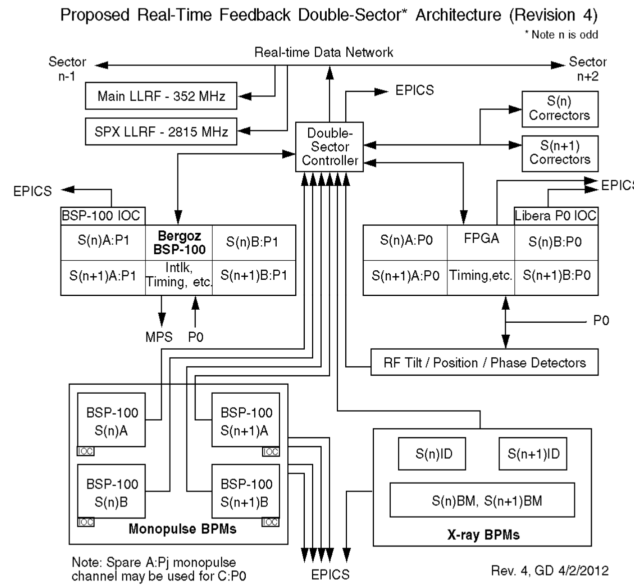

Figure 1: Proposed RTFB system architecture.

SYSTEM CONTROL ALGORITHM

The existing APS orbit correction has two systems that operate in parallel: slow orbit correction and fast orbit correction. The former is called global DC orbit correction and latter is the real-time feedback system. The two systems are decoupled by first-order low-pass and high-pass filters, respectively. The upgraded system will integrate the two systems.

The orbit correction algorithm for the orbit feedback system is based on the analysis of the response matrix using the technique of singular value decomposition (SVD) of matrices. The mathematical formulation of the SVD of matrices is broadly available in literature [2].

Let **x**[n] denotes the M-tuple vector of BPM readings at discrete time index n. Let **Δx**[n] be the orbit error between reference orbit **b**[n] (BPM set point) and BPM reading. The beam motion **Δx**[n] is affected by disturbances, which are denoted by **w**[n] and orbit correction via corrector dipoles. That is:

$$\mathbf{\Delta x}[\mathrm{n}] = H_B(R\mathbf{\Delta c}[\mathrm{n}] + \mathbf{w}[\mathrm{n}]), \quad (1)$$

where R is the M-by-N response matrix and **Δc** [n] is the corrector strength change.

The system diagram is shown in Figure 2.

* Work supported by U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.
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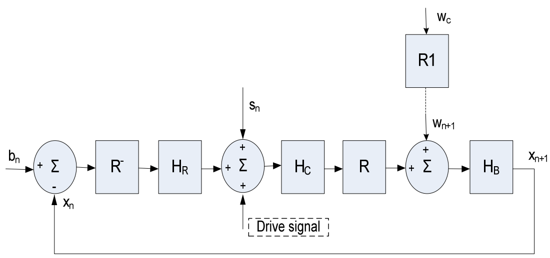

Figure 2: System diagram.

In Figure 2, R^- is the pseudo-inverse response matrix, H_R is a PI controller, H_C is fast corrector dynamics, H_B is the BPM electronics, b_n is the BPM set point, s_n is the corrector current set point, w_n is the external perturbation, and w_c and R1 are the simulated noise and response matrix, respectively.

The difference equation of the above system can be described as

$$x_{n+1} = H_B \cdot \left(R \cdot H_C \cdot \left(S_n + H_R \cdot \mathrm{R}^- \cdot (\mathrm{b_n} - \mathrm{x_n})\right) + w_{n+1}\right). \quad (2)$$

The z-transform of the equation is

$$\mathbf{X}(\mathrm{z}) = \left\{I - \mathbf{F}(z)\frac{1}{\mathbf{H_B}(z)}\right\}\mathbf{B}(z) + \mathbf{F}(z)\mathrm{R}\mathbf{H_C}(z)\mathbf{S}(z) + \mathbf{F}(z)\mathbf{W}(z), \quad (3)$$

where

$$\mathbf{F}(z) = \frac{1}{\mathrm{I}+z^{-1}\mathbf{H_B}(z)R\mathbf{H_C}(z)\mathbf{H_R}(z)\mathrm{R}^-}\mathbf{H_B}(z). \quad (4)$$

The last term in Eq. (3) quantifies the effect of the RTFS in rejecting the disturbances:

$$\mathbf{\Delta X}(\mathrm{z}) = \mathbf{F}(z)\mathbf{W}(z). \quad (5)$$

The system control goal is to minimize the spatially averaged beam motion power spectrum density (PSD) over some frequency band Ω [3]. $1/\mathrm{M}\ \left\|\mathbf{\Delta x}(e^{j\omega})\right\|_2^2$ is the spatially averaged beam motion power spectrum. It is noted that

$$\left\|\mathbf{\Delta x}(e^{j\omega})\right\|_2^2 = \mathbf{\Delta x}^*(e^{j\omega})\mathbf{\Delta x}(e^{j\omega}) \text{ and} \quad (6)$$

$$\frac{1}{M}\left\|\mathbf{\Delta x}(e^{j\omega})\right\|_2^2 = \frac{1}{M}\mathbf{w}'(e^{-j\omega})\mathbf{F}'(e^{-j\omega})\mathbf{F}(e^{j\omega})\mathbf{w}(e^{j\omega}). \quad (7)$$

W is simulated by noise **Wc** and M-by-N1 response matrix R1:

$$\mathbf{W}=\mathrm{R1}\mathbf{Wc}. \quad (8)$$

N1 is the number of available correctors in the storage ring. **Wc** is the colored white noise, which has the same spectrum as the averaged open-loop noise in the storage ring.

LABORATORY MEASUREMENT

The spatially averaged disturbance and fast corrector's transfer function have been measured in the present APS storage ring real-time feedback system and are used in the simulations.

Beam Motion Measurement

According to Eq. (1), the beam motion measured on the BPM is equal to its disturbances there if there is no corrector strength change. Therefore the spatially averaged open-loop beam sample's noise PSD can represent the spatially averaged disturbance PSD. The open loop PSD data and its smooth estimate of the data are shown in Figure 3.

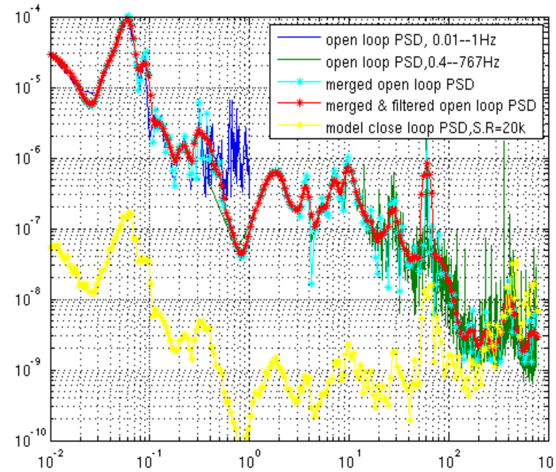

Figure 3: Open-loop disturbance PSD.

Fast Corrector's Transfer Function

A laboratory measurement has been set up at sector 38 of the APS storage ring to measure the transfer function of the fast corrector dynamics. The setup is shown in Figure 4. An Agilent 35670A Dynamic Signal Analyzer was used to make the measurements. The corrector was driven with ± 1A signal with 10-A offset to avoid going through 0 A. The frequency for the sine signal swept is 1 Hz to 10 kHz. The BPM signal was taken from the cable that feeds the analog position to BSP100. The filter comparator has a band-pass filter with 10-MHz bandwidth centering at 352 MHz. The monopulse receiver has a bandwidth over 1 MHz. The major contribution for the measured transfer function is from the fast corrector dynamics. The MATLAB output error (OE) model parameter estimation function was used to generate transfer function from the measured data.

A 4-pole OE model was generated for both horizontal and vertical fast correctors. The frequency responses for the measured data and the fitting model for horizontal correctors are shown in Figure 5.

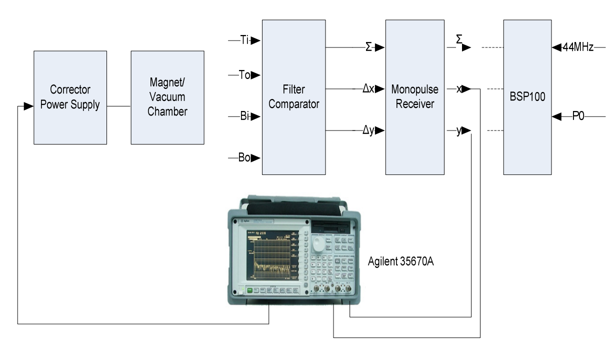

Figure 4: Measurement setup for the fast corrector dynamics.

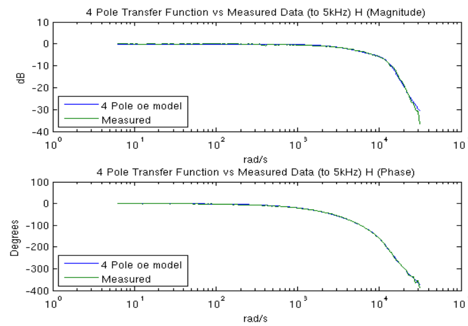

Figure 5: Frequency response from measured data and OE model for horizontal fast corrector at S38.

SIMULATION RESULTS

Regulator Tuning

The PI controller is used as the system regulator. A MATLAB simulink block was designed to tune the regulator parameters as shown in Figure 6. The transport delay is used to simulate 1 tick computation delay. The tuning criteria for three different sampling rates 1.5, 10, and 20 kHz is: the gain margin is about 10 db; the phase margin is about 60 degree.

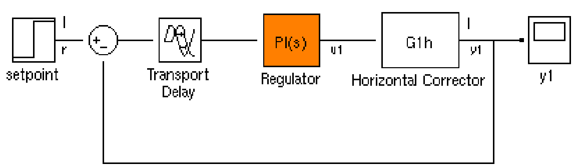

Figure 6: Simulink block for regulator tuning.

Simulation for Upgraded System

The simulation was done in MATLAB. To simulate the APS real-time feedback upgrade, all the A:H(V)3 and B:H(V)4 correctors are assumed as fast correctors. 320 BPMs are used for each plane. The APS OAGapps tool is used to generate the response matrix and the inverse response matrix. The open loop noise spectrum was generated by SDDS tools using measured data. The simulated noise has the same spectrum as the open loop noise with adjustable gain and random phase.

The fast corrector's transfer function in continuous form in Eq. (9) is changed to a discrete form using the MATLAB c2d command:

$$\text{horizontal TF} = \frac{3.965e^{7}s^{2} - 1.39e^{12}s + 3.275e^{16}}{s^{4} + 58320s^{3} + 8.774e^{8}s^{2} + 1.026e^{13}s + 3.336e^{16}}. \quad (9)$$

The APS storage ring has several types of BPM electronics that were simulated by different low-pass filters.

The close-loop beam motion PSD is obtained according to Equations (7) and (8). The beam motion PSD and cumulative RMS for the horizontal and vertical planes at the different sampling rates 1.5, 10, and 20 kHz are shown in Figures 7 and 8, respectively.

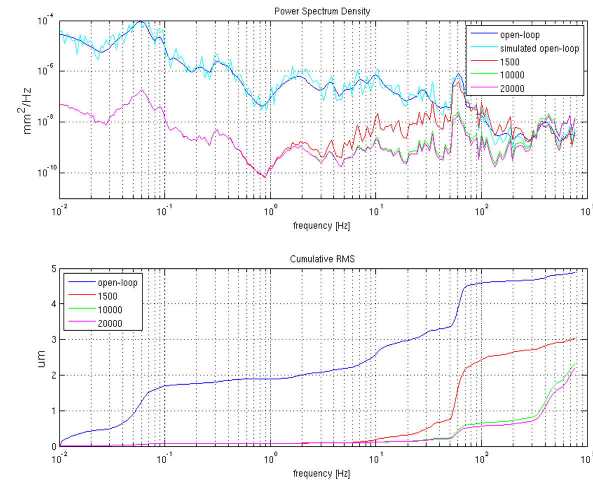

Figure 7: The beam motion PSD and cumulative RMS for the horizontal plane.

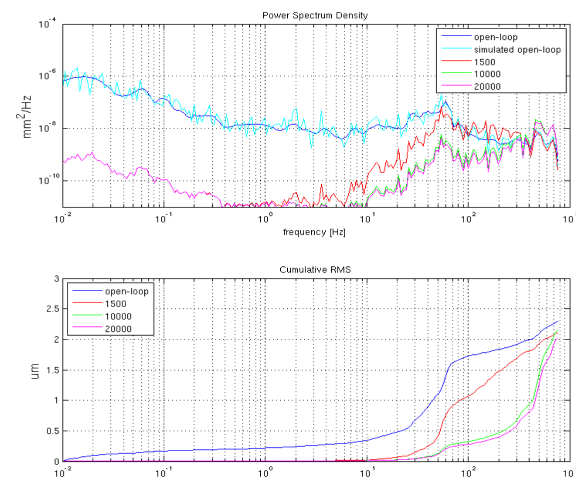

Figure 8: The beam motion PSD and cumulative RMS for the vertical plane.

CONCLUSION

With 320 BPMs and 78 fast correctors, the simulation study shows that the beams stability at orbit correction band 0.01-200 Hz and 20 kHz sampling rate can be 0.7 µm and 0.4 µm for horizontal and vertical planes, respectively.

ACKNOWLEDGMENTS

The authors wish to thank John Carwardine of APS for technical insight and useful discussions.

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