

TIME-DOMAIN SIMULATION SOFTWARE FOR THE APS STORAGE RING REAL-TIME ORBIT FEEDBACK SYSTEM UPGRADE *

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Abstract

The APS storage ring real-time feedback (RTFB) system will be upgraded as part of the Advanced Photon Source (APS) Upgrade project. Time-domain simulation software was implemented to optimize feedback system parameters and evaluate the performance of different feedback system configurations. The software includes two parts: a corrector noise model generator and the RTFB simulation. The corrector noise model generates realistic beam motion based on turn-by-turn BPM measurements of the actual storage ring orbit. The noise model orbit motion data is then used as input for the RTFB simulation. This paper introduces the noise model and RTFB system algorithms as well as high-level software used to realize the noise model and feedback system simulation.

INTRODUCTION

The existing APS has two feedback orbit correction systems that operate in parallel: slow orbit correction using slow correctors is effective up to 1 Hz and fast orbit correction that is effective up to 60 Hz horizontally and 100 Hz vertically. The fast correction systems use a limited number of correctors with special vacuum chambers that extend the usable bandwidth of each fast corrector to 800 Hz. The upgraded system will integrate the two systems into one feedback system as well as increase the sampling rate from 1.5 kHz to 22.6 kHz. S. Xu *et al.* [1] did an initial feedback simulation in the frequency domain using MATLAB, which simulated orbit motion using a model derived from BPM measurements. This paper builds on these ideas and introduces a time-domain simulation that is integrated with software used to operate, control, and configure the existing storage ring feedback system.

The simulation is broken into two parts: the noise model and the feedback simulation. The noise model uses turn-by-turn data from field-programmable gate array (FPGA) [2] BPMs to model real orbit motion in the storage ring. The feedback simulation then takes the modeled open-loop beam motion calculated from the noise model as input to test various feedback algorithms and corrector-BPM configurations. The APS ring has 40 sectors, 36 of which have been upgraded to FPGA BPMs. The final 4 sectors of FPGA BPMs will be installed by January 2014. Each storage ring sector has 7 FPGA BPMs used by the noise model. The APS SR ring has a total of 470 BPMs.

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A tool for collecting FPGA BPM turn-by-turn history data was developed and used to supply the noise model with orbit position information.

CORRECTOR NOISE MODEL

The noise model algorithm generates corrector drive setpoints by multiplying turn-by-turn FPGA BPM data by a user-specified inverse response matrix (IRM). These setpoints are used to compute the beam position at every BPM by multiplying by the forward response matrix (RM). The correctors used to generate the simulated beam motion using the IRM are not used for feedback. In fact, we usually compute corrector drive setpoints using 3 correctors per sector, which has the effect of approximating the average beam motion through the sector as recorded by the 7 FPGA BPMs. In computing corrector drive setpoints, all FPGA BPMs in each sector are used except for those not yet installed and a few that are not connected or otherwise disabled. The simulated beam motion data was created as follows:

1. Process measured FPGA BPM turn-by-turn noise data, filter out those BPMs whose standard deviation or offset exceed the given limit, and select the good BPM data for use.
2. Create an inverse response matrix (IRM) using `sddspseudoinverse` [3] with chosen correctors and good BPM data sets found in step 1.
3. Create forward response matrix (RM) with the correctors selected in the IRM and all APS storage ring existing BPMs.
4. Compute the corrector turn-by-turn drive settings with the IRM computed in step 2 and the measured BPM turn-by-turn data.
5. Compute the beam position at every BPM with the RM generated in step 3 and corrector drive computed in step 4. The computed beam position at every BPM will be used in the feedback simulation.

When generating the IRM using singular value decomposition (SVD) all singular values are used since the number of correctors is small compared to the number of FPGA BPMs used. Alternatively, one could use few singular values and more correctors and end up with similar average simulated beam motion for use by the feedback simulation. The best way to create beam motion from actual data continues to be

the subject of investigation. Figure 1 shows typical reconstructed BPM data generated by the noise model compared to the actual measured data. The software can add addi-

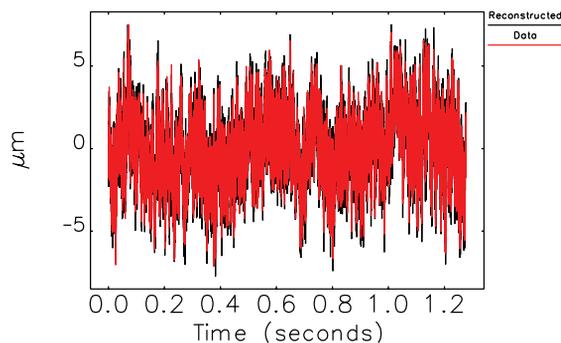


Figure 1: S8B:P5 x plane measured data compared to reconstructed BPM data generated from the noise model.

tional noise to the generated BPM data based on the different BPM types installed in the machine. We also added the ability to only use a subset of the full FPGA BPM time-domain data sets for faster simulation and post-processing.

TIME DOMAIN RTFB SIMULATION

The feedback simulation uses a user-selectable configuration of correctors and BPMs to simulate feedback correction on modeled orbit motion obtained from the noise model. Typically to model what is presently done with the installed storage ring RTFB system, all fast correctors, a variety of slow correctors, and approximately twice as many BPMs as correctors are chosen to simulate feedback. However, the software allows choosing any combination of BPMs and correctors. Typically, the set of correctors used is different from those used in the noise model. SVD is used to compute the inverse response matrix for the correction configuration, with removal of small singular values. The software for doing this is identical to that used to configure the installed feedback system in the storage ring. The simulation steps, illustrated in Figure 2, are as follows:

1. Add the corrected BPM orbit of the previous turn ($N-1$) to the N th turn initial BPM orbit that generated by the noise model; the result gives the N th turn BPM orbit input. For the first turn ($N=1$), the BPM orbit input is the first turn of the initial BPM orbit.
2. Multiply the N th turn feedback BPMs by the feedback inverse response matrix. This gives the N th turn feedback corrector errors. The feedback BPMs orbit is a subset of the BPM orbit.
3. Apply the regulator plus corrector model on the N th turn corrector errors and generate the N th turn corrector drive setpoints.
4. Multiply the N th turn corrector drive setpoints by the response matrix and generate the N th turn corrected BPM orbit for all BPMs. For the next turn, increase the turn N by 1, continue to step 1.

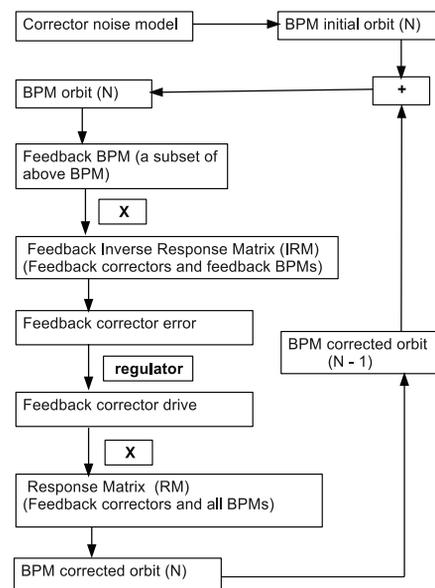


Figure 2: Illustration of time-domain APS feedback simulation.

The feedback simulation is implemented in C using the regulator and corrector response coefficients. The critical part of the feedback simulation is how to obtain the regulator's coefficients. A MATLAB script is used to compute the coefficients from the measured corrector transfer function in the frequency domain along with the regulator's control parameters K_p and K_i , where K_p and K_i were obtained using the MATLAB PID tuning tool. Due to the license limitations of MATLAB, we replaced the MATLAB script with an octave script for deriving the time-domain regulator coefficients from the frequency domain parameters. We also added corrector time delay to the regulator coefficients, so that we can study the impact of corrector time delay on the feedback system. Although the octave control package does not have a time delay function that includes fractional delays, it is straightforward to implement a delay that is some integer times the sampling period in the regulator. The sampling rate used in the simulation is 22.6 kHz, so the sampling period is about 44 microseconds. Some feedback simulation results are discussed in the next section.

SIMULATION RESULTS

To test the simulation software, a configuration with one horizontal BPM (S12A:P2) and one horizontal corrector (S12A:H3, next to S12A:P2) was selected for feedback correction. The simulation result in Fig. 3 shows that S12A:P2 is corrected by about a factor of 100 at around 10 Hz, diminishing to no correction at approximately 200-300 Hz. The other BPMs show no such suppression since the single corrector is only effective at suppressing beam motion at adjacent BPMs. This test confirmed basic operation of the feedback to suppress beam motion.

Next, a square matrix with 78 horizontal BPMs (A:P1 and B:P0) and 78 horizontal correctors (A:H2 and B:H2) was used to test the feedback simulation. The results show that not only the beam motion at the A:P1 and B:P0 BPMs

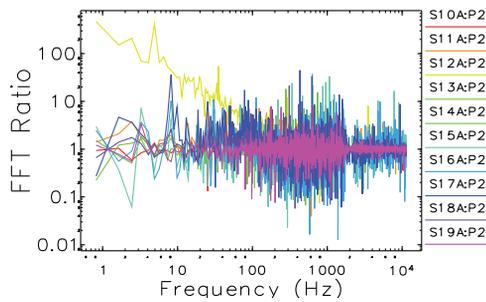


Figure 3: The FFT ratio of the uncorrected vs corrected orbit at some APS A:P2 BPMs using the feedback configuration of one corrector (S12A:H3) and one BPM (S12A:P2).

is corrected but also beam motion at the A:P2 BPMs (which are not part of the correction configuration) is corrected as shown in Fig. 4. The orbit motion suppression is seen to extend out to approximately 200 Hz from the figure.

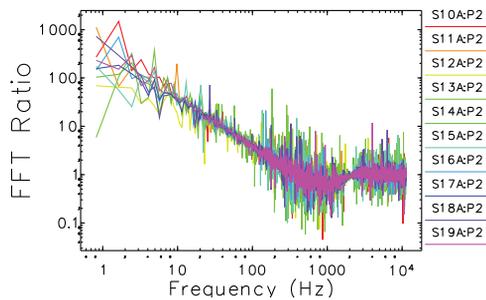


Figure 4: The FFT ratio of the raw and corrected orbit of some APS A:P2 BPMs.

We then tested the effect of applying a time delay to the simulation via modification of the regulator and corrector filter coefficients. Figure 5 shows the results. As the delay is increased the orbit motion increases in a band from about 200 Hz to 1 kHz with a peak (minimum) at about 550 Hz. In this band, the phase of the correction relative to open loop orbit motion acts to enhance rather than suppress the motion. In addition to the FFT analysis, the software also

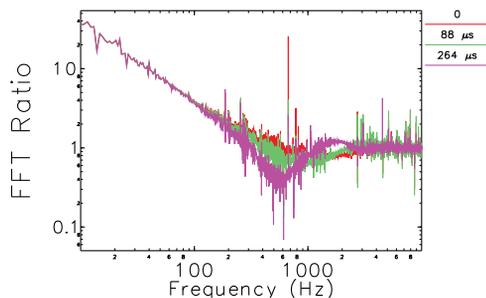


Figure 5: The FFT ratio of the raw and corrected orbit of APS S10A:P1 BPM at different delays.

has PSD analysis of BPM position and corrector drive set-

points. For example, Fig. 6 shows the PSD of the horizontal S10A:P1 BPM before and after feedback correction. The PSD analysis shows that the feedback correction is able to correct the orbit up to 500 Hz.

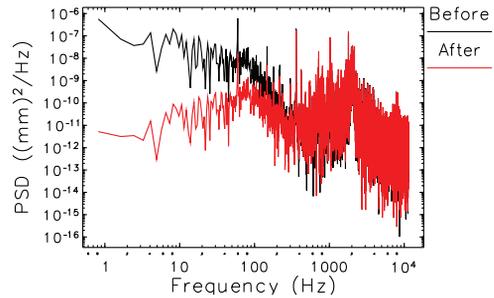


Figure 6: The PSD of APS horizontal S10A:P1 BPM before and after feedback correction.

SUMMARY

APS storage ring feedback simulation software was implemented with C, MATLAB/octave, and Tcl/Tk. The feedback correction is implemented in C. A MATLAB/octave script is used to derive the regulator coefficients in time domain from the frequency domain parameters, and the Tcl/Tk script is used for the graphical user interface. We use the same correction configuration software as the actual RTFB system installed in the storage ring.

The simulation results show that the feedback correction band can be up to 200 Hz with 22.6 kHz sampling rate using various BPM and corrector configurations. The simulation can model the corrector response as well as allow us to tune regulator control parameters K_p and K_i for optimum orbit motion suppression. Regulator optimization will be implemented in the near future. We also plan to do detailed simulations of actual machine RTFB corrector-BPM configurations and compare the results to the results measured for the presently installed RTFB system.

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