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COUPLED BUNCH MODE ZERO CORRECTION WITHIN THE ORBIT FEEDBACK BANDWIDTH *

P. Kallakuri†, A. Brill, J. Carwardine, L. Emery and N. Sereno
Argonne National Lab, Lemont, USA

Abstract

The fast orbit feedback (FOFB) bandwidth for Advanced photon source upgrade (APS-U) will be DC-1 kHz and the synchrotron frequency will be between 100-560 Hz. This frequency overlap places coupled bunch mode 0 (CBM0) induced horizontal orbit motion inside the orbit feedback bandwidth, potentially affecting our ability to achieve beam stability goals. Longitudinal feedback kicker is not strong enough to damp CBM0 oscillations. We developed new beam-based feedback method to suppress CBM0 oscillations with low level RF phase as actuator. It uses existent FOFB framework with no changes to the feedback algorithm. Effectiveness of this method is verified using present APS operations lattice where synchrotron frequency is outside orbit feedback bandwidth. In the present work, low alpha lattice is created to emulate APS-U setting where synchrotron frequency is inside the orbit feedback bandwidth. Experiments with this lattice successfully demonstrated CBM0 correction within orbit feedback bandwidth. Combined operation of orbit feedback and CBM0 correction is stable, and CBM0 oscillations are damped. We achieved better orbit motion suppression and corrector drive efforts are reduced as well.

INTRODUCTION

The target bandwidth of the Advanced Photon Source Upgrade (APS-U) Fast Orbit Feedback (FOFB) is DC-1000 Hz where the synchrotron tune will be between 100-560 Hz. This overlap places Coupled Bunch Mode 0 (CBM0) induced horizontal position offsets within the FOFB bandwidth range, affecting APS-U goals for beam stability. Large storage-rings such as APS would need longitudinal feedback system with high kick voltage capability for CBM0 suppression. APS-U longitudinal feedback kicker is not strong enough to damp CBM0 oscillations. We developed new orbit to RF phase feedback method using existent orbit feedback framework with no additional processing hardware requirements [1]. It operates at the Low Level RF (LLRF) signal level of the main RF system and does not require high kick voltages. Based on synchrotron oscillation theory [2,3], we derived relationship between beam position deviation at dispersive BPMs and RF phase noise that represents the open loop dynamics of our feedback configuration. An analytical model is devised for the coupling mechanism of synchrotron oscillations to transverse orbit through dispersion. It allows an energy-induced component to be extracted from the measured orbit which is derivative of the RF phase error. Using this the orbit feedback controller generates a RF phase control signal as another drive signal in the orbit feedback algorithm. Experiments conducted at the present APS storage ring using 7 GeV operations lattice and APS-U prototype fast orbit feedback controller [4,5] demonstrated the effectiveness of this method at damping coupled bunch mode zero oscillations.

In the above experiments [1] the synchrotron frequency (2.2 kHz) and orbit feedback bandwidth (920 Hz) are well separated. We continued our study using low-alpha lattice configuration developed to mimic APS-U setting where, synchrotron frequency (60 Hz) is within the orbit feedback bandwidth (90 Hz). We would be able to study the interaction of both feedbacks more clearly in this setup. The storage-ring energy is set to 6 GeV and low momentum compaction factor of $3.6 \cdot 10^{-06}$ is used to get synchrotron frequency to around 60 Hz. Orbit feedback with 1.5 kHz sampling rate used for APS operations is termed as Real Time Feedback (RTFB) [6]. Experiments with low-alpha lattice are conducted using RTFB system so that we would be able to use 38 fast correctors and 154 BPMs around the ring. With the prototype system we could only use 3 fast correctors and 12 BPMs in 2 sectors that is not adequate to deal with larger noise seen in low-alpha lattice. Details of our experimental setup with RTFB controller, closed loop performance of orbit to RF phase feedback, and results from the simultaneous operation of RTFB and CBM0 correction with low alpha lattice are presented in next sections.

EXPERIMENTAL SETUP

Closed loop schematic of RTFB together with orbit to RF phase feedback is shown in Figure 1. RTFB controller hardware only allows use of total 160 BPMs (4 per sector) for orbit feedback computations. We used 154 BPMs for beam position measurements. Orbit feedback uses 38 horizontal fast correctors, and orbit to RF phase feedback is integrated into RTFB framework by repurposing fast corrector (S40A:H3) analog drive signal as phase drive. DAC output channel of S40A:H3 is connected to LLRF system [7] phase input. The cavity phase loop bandwidth is adequately greater than the synchrotron oscillation frequency. So the RF system is considered as simple gain term in the feedback model. PID_rtfb controller is used orbit correction and PID_rfPh controller is used for CBM0 correction. Same feedback algorithm that generates corrector power supply set-points is used for phase drive. Phase computations are incorporated as additional row in Inverse Response Matrix (IRM) dot product. Horizontal BPM position vector **x** is

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† pkallakuri@anl.gov

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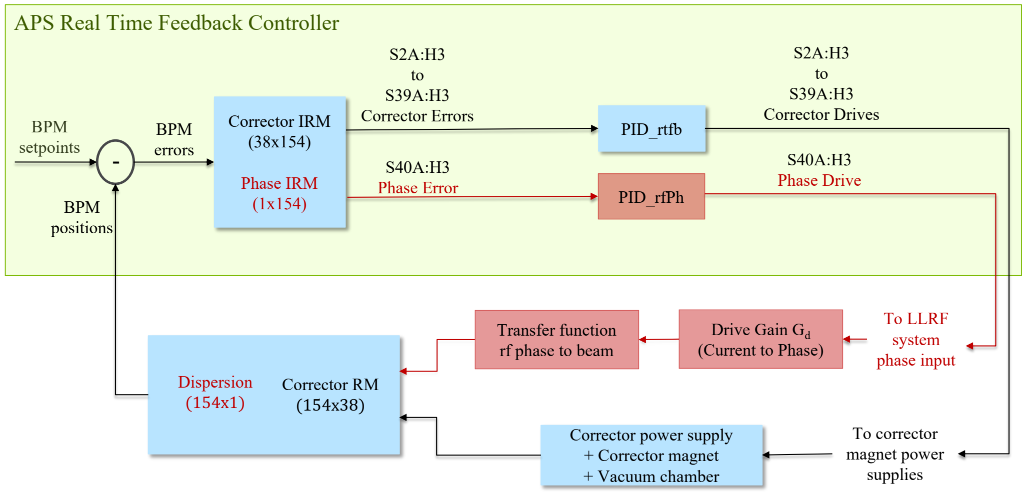

Figure 1: Experimental setup for simultaneous operation of RTFB and orbit to RF phase feedback using APS RTFB system.

obtained from 154 BPMs. Phase error is calculated as dot product of measured orbit and weighted dispersion vector *Phase_IRM* as defined in Eq. (1). α_c is the momentum compaction factor, ω_{rf} is RF angular frequency, and η is the dispersion vector.

$$Phase\_IRM = \frac{180}{\pi}\frac{1}{G_d}\frac{\omega_{rf}\alpha_c}{\eta\cdot\eta}\eta \qquad (1)$$

Drive gain $G_d = \frac{1}{13}$ is to convert phase drive in amperes to RF phase set-point in degrees. Phase IRM (1x154) computed from Eq. (1) and Corrector IRM (38x154) obtained from orbit response matrix are concatenated as 39x154 IRM used in the experiments. For beam-based studies we used 6 GeV low alpha lattice with storage-ring current of 14 mA in 24 bunch operation and 24 mA in 48 bunch operation. Relatively low currents are used since it was very difficult to inject into this lattice. So, beam loading is negligible.

ORBIT TO RF PHASE FEEDBACK FOR CBM0 CORRECTION

First step in our experiments is to establish LLRF phase set-point control from RTFB controller in open loop, and then verify the stability of orbit to RF phase feedback and suppression of synchrotron frequency magnitude in closed loop. For open loop measurements S40A:H3 drive signal is the input, and beam phase response is the output. Figure 2 shows the step input to phase drive, and measured beam phase response. Input step of 20 A resulted in 1.6° change in RF phase response confirming drive gain $G_d = \frac{1}{13}$. Large 360 Hz noise from klystron power supply is seen in the steady state RF phase.

CBM0 Correction in Closed Loop Operation

After testing the open loop drive setup, studies are conducted with closed loop orbit to RF phase feedback configuration using 1x154 phase IRM. The storage ring configuration for this test is 24 bunches, 14 mA, 6 GeV low alpha lattice with synchrotron frequency at 60 Hz. Closed loop

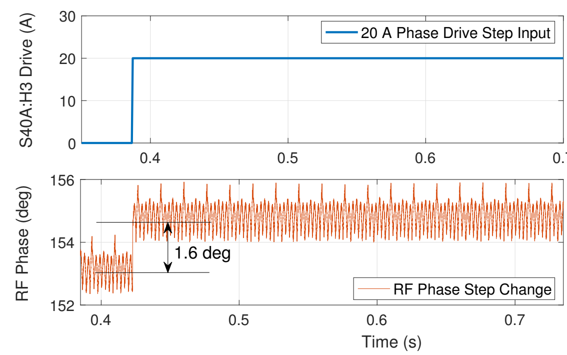

Figure 2: Open loop phase step response measured for 20 A input step amplitude.

is stable with negative proportional gain and we achieved suppression around synchrotron frequency. We tested K_p gains in the range -0.01 to -0.06, the beam was unstable beyond -0.06. Motion at 360 Hz.

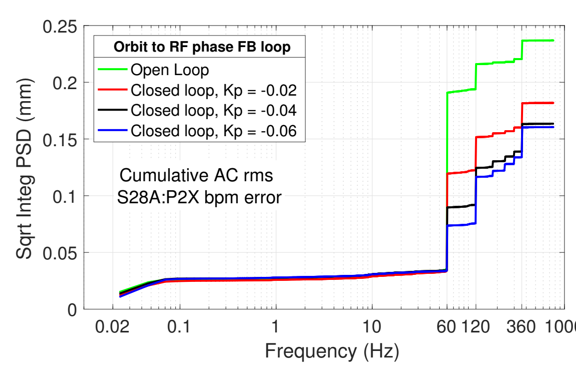

Figure 3: Orbit motion measured in open loop, and closed loop with different proportional gain values.

Figure 3 shows square root integrated Power Spectral Density (PSD) of BPM error for open loop and closed loop with different K_p gain values. Orbit motion suppression at synchrotron frequency (60 Hz) is observed when the feedback is ON. Increase in proportional gain resulted in more suppression at synchrotron frequency.

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REAL TIME FEEDBACK WITH COUPLED BUNCH MODE ZERO CORRECTION

Next step in our experiments is to study interaction between CBM0 correction and RTFB during the simultaneous operation of both feedbacks.The test configuration is 6 GeV low alpha lattice with 48 bunches and 24 mA storage-ring current. Synchrotron frequency 60 Hz is within the orbit feedback bandwidth of 90 Hz emulating APS-U settings.

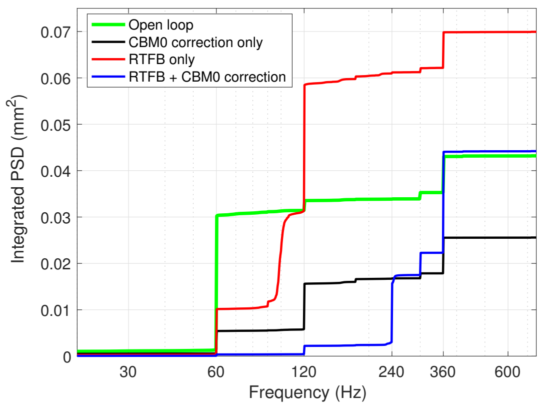

Figure 4: Comparison of cumulative mean square orbit motion at S28A:P2X BPM for different feedback configurations.

Closed loop with unified 39x154 IRM is stable with proportional controllers. For RTFB we used K_p gains in the range 0.01 to 0.03, and for orbit to RF phase feedback we used K_p gains in the range -0.01 to -0.05. For individual operation optimum performance is achieved with maximum permissible K_p gains in each case. For simultaneous operation we tuned the gains together for optimum performance. For RTFB $K_p = 0.02$, and for CBM0 correction $K_p = -0.03$ are the optimal gains. The angle between dispersion and betatron closed orbits with 154 BPMs are in the range $83 - 97°$ which is comparable to 440 BPMs case shown in Ref. [1].

We are working on a simulation study to further understand whether this near orthogonality is inferring complete decoupling when both corrections has a frequency overlap. BPM noise response data is measured for different feedback configurations: open loop, CBM0 correction only $K_p = -0.05$, RTFB only $K_p = 0.03$, RTFB $K_p = 0.02$ + CBM0 correction $K_p = -0.03$. Integrated PSD of BPM error in different feedback configurations is shown in Figure 4. Open loop orbit motion shows significant spike at 60 Hz, which is suppressed in all three closed loop configurations: RTFB only, CBM0 correction only, and RTFB + CBM0 correction. During individual operation, orbit to RF phase feedback and RTFB are correcting respective energy and betatron components at synchrotron frequency which resulted in partial suppression at 60 Hz. High frequency motion beyond 90 Hz is amplified during RTFB only operation. Motion at 120 Hz is amplified when only CBM0 correction is used. With both feedbacks running together we got significant suppression at 60 Hz due to the combined effect. Also, high frequency motion amplified by individual feedback operation is attenuated up to ≈220 Hz. Motion at 360 Hz is not suppressed by orbit to RF phase feedback. Perturbation at 360 Hz is in phase with RF phase modulation whereas perturbation at synchrotron tune is 90° out of phase. So, we would need large controller gains to affect 360 Hz which could be beyond the stability limit of synchrotron frequency damping.

BPM responses are measured at all 154 BPMs around the storage-ring to analyze envelope of the orbit motion. Figure 5 shows power spectral density plots of measured BPM errors in open loop and different closed loop configurations. All BPM responses showed similar frequency response pattern, while BPMs in the high dispersion area has larger magnitudes compared to others. Individual operation of RTFB or CBM0 correction partially suppressed 60 Hz and frequencies beyond 90 Hz are amplified. During combined

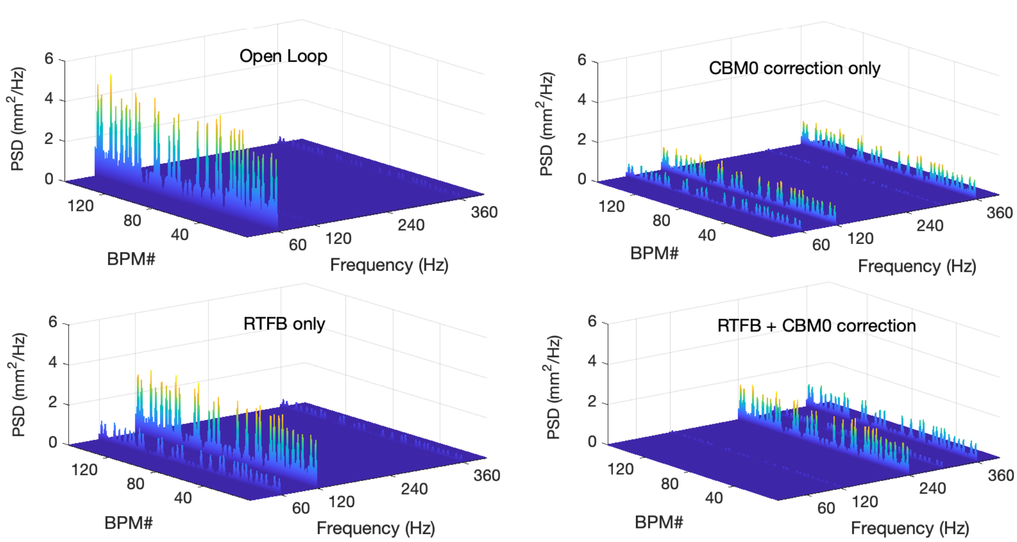

Figure 5: PSD of BPM errors at all 154 BPMs around the storage ring. Comparison of responses in open loop and different closed loop configurations.

operation significant suppression at 60 Hz and better orbit motion suppression up to 240 Hz is achieved. APS RF system has noise at 360 Hz and other 60 Hz harmonics. These frequencies have larger amplitudes in low alpha lattice configuration. Hence narrow resonant increase of noise at 60 Hz harmonics is seen when high frequency motion is amplified during individual and combined feedback operation.

Analysis of Feedback Control Efforts

Feedback control effort is the input to the actuator from the dynamic controller to perform necessary correction. Reduction in control efforts is beneficial to the feedback operation.The corrector and phase drive signals in our case indicate the control efforts. In order to analyze the drive efforts of both feedbacks we used cumulative mean square of phase and 38 corrector drive signals. Integrated PSDs of drive signals during individual operation of each feedback and combined operation of both feedbacks are shown in Figure 6. Drive magnitudes during individual operation

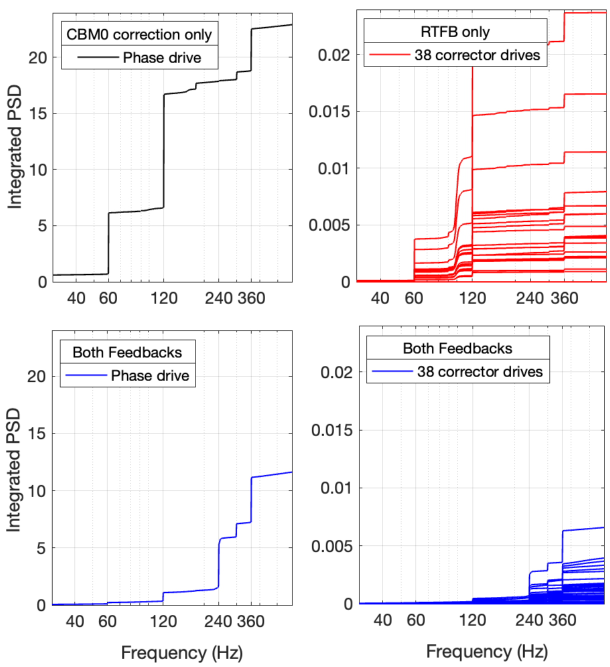

Figure 6: Comparison of drive efforts of each feedback individual operation with drive efforts in simultaneous operation.

are larger compared to simultaneous operation. During individual operation the feedbacks see large error at synchrotron frequency which results in more drive effort as the feedback keeps trying to correct the error. When CBM0 correction and orbit feedback are operated together both energy and betatron components are corrected simultaneously, and the error will be small. As a result phase and corrector drive magnitudes for frequencies below 120 Hz are significantly reduced in combined operation, and drive magnitudes up to Nyquist frequency are also less compared to respective individual operations. From these results we can say that the combined operation is aiding in control effort reduction of both feedbacks.

CONCLUSIONS

We successfully demonstrated CBM0 correction within the orbit feedback bandwidth. We used 6 GeV low-alpha lattice that provides a test setup where synchrotron frequency (60 Hz) is within the RTFB bandwidth (90 Hz) similar to APS-U configuration. First, we established LLRF phase set-point control from RTFB controller open loop and then verified the stability in closed loop. Orbit to RF phase feedback loop is stable and we achieved suppression around synchrotron frequency. Closed loop operation with both feedbacks using unified corrector and phase IRM is stable with proportional controllers. During individual operation, orbit to RF phase feedback and RTFB are correcting respective energy and betatron components at synchrotron frequency which resulted in partial suppression at 60 Hz. Orbit feedback was effective at reducing motion at synchrotron frequency, but did so at the expense of increasing broadband rms motion beyond the open-loop level. This was consistent with previous RTFB operating experience. Running CBM0 correction on its own also reduced motion at synchrotron frequency and without increasing the broadband rms motion. The combination of CBM0 correction and RTFB was significantly more effective than RTFB alone over all frequency bands from DC to 360 Hz. Feedback drive efforts are also reduced during combined operation of RTFB and CBM0 correction.

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