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CLOSED LOOP MODELING OF THE APS-U ORBIT FEEDBACK SYSTEM*

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Abstract

Orbit stabilization to 10% of the expected small beam sizes for Advanced Photon Source Upgrade (APS-U) requires pushing the state of the art in fast orbit feedback (FOFB) control, both in the spatial domain and in dynamical performance. We are building a Matlab/Simulink fast orbit feedback system model to guide decisions about APS-U fast orbit feedback system implementation and to provide a test bench for optimal-control methodologies and orbit correction algorithms applicable to the APS-U. A transfer function model was built from open-loop frequency-response and step-response measurements of the present APS and subsequently validated against closed-loop measurements. A corresponding model for APS-U fast orbit feedback was generated by substituting measured responses of APS-U prototype corrector magnets and power supplies into this same model. Stabilizing PID gains are designed using model, and simulated dynamic performance of the new controller is validated through experiments.

INTRODUCTION

A new orbit feedback system is under development for the APS Upgrade, where the expected beam sizes are 13 μm and 2.8 μm for horizontal and vertical planes respectively. This new system will use a distributed array of DSPs to compute orbit corrections at 22.6 kHz (12x faster than the present system) and a matrix of 560 bpms and 160 correctors. The target unity-gain bandwidth is 1 kHz. Orbit stability requirements for the upgrade are considerably more stringent than the present APS where the regulator uses just the integral term (K_i) of a classical PID, and is tuned for minimum residual broad-band rms orbit motion [1]. A higher K_i than optimal gives better attenuation at lower frequencies but comes at the expense of amplifying residual motion at higher frequencies. Also, once the correctable modes have been reduced below the level of the noise floor, there is little to be gained from further increasing K_i gain. We need to investigate control design methods (beyond classical PID tuning) in advanced control theory that are applicable to electron beam stabilization to learn the performance benefits.

We are building a Matlab/Simulink fast orbit feedback system model to provide a test bench for optimal-control methodologies and orbit correction algorithms. First step is to model the open loop dynamics of the prototype feedback system developed in APS Sector 27/28 for beam stability studies [2]. This system uses present storage ring corrector magnets. The modeling results are tested and validated against this prototype before developing the predictive model for APS-U [3]. Next step is to develop a closed loop model using estimated dynamics and accelerator response matrix, and validate model performance with measurements. Since the model application in our case is to use it for control design, it is important to verify how close our model based controller design results match the actual system performance. We design PID gains for stabilizing the model and compare the predicted performance with designed gains against measurements.

FAST ORBIT FEEDBACK SYSTEM CLOSED LOOP MODEL

Layout of the closed loop Fast Orbit FeedBack (FOFB) dynamic model developed in matlab/simulink is shown in Fig. 1. Main components included are open loop dynamic model, spatial response matrix, and DSP controller schematic. Significant elements of the controller model are IRM, and the regulator with LPF, HPF and digital PID controller. Four input - Four output closed loop configuration (4 fast correctors to 4 P0 bpms in S27/28) is used for results shown in this paper. Open-loop dynamic model $H[z]$ is estimated using beam based time and frequency measurements (system identification process is detailed in [3]). It includes the dynamics of the power supply, magnet, vacuum chamber and bpms. Based on a-priori knowledge of the physical components, $H[z]$ is separated into 2 components. Transfer function of the present corrector magnet with vacuum chamber $H_M[z]$, and rest of the open loop dynamics $H_1[z]$ (dominated by power supply).

$$H[z] = H_1[z] \cdot H_M[z] \tag{1}$$

$$\begin{aligned} H_M[z] &= \frac{-0.000112(1-14.78z^{-1})(1-0.97z^{-1})}{(1-0.73z^{-1})(1-0.98z^{-1})(1-0.82z^{-1}+0.40z^{-2})} \\ H_1[z] &= \frac{(1+2.11z^{-1}+6.12z^{-2})}{(1+0.75z^{-1}+0.36z^{-2})} \end{aligned}$$

Time Domain Response Validation

The closed loop model is first validated by comparing the model step responses against measurements with integral gain (K_i). Step bump of 50 μm is given to BPM set points of 2 P0 bpms using AFG 1, output measured is *BPM Readback* signal. Model responses are in good agreement with measurements in both planes, horizontal response comparisons are as shown in Fig. 2. Measured horizontal BPM response has small perturbation in steady state which is not present in

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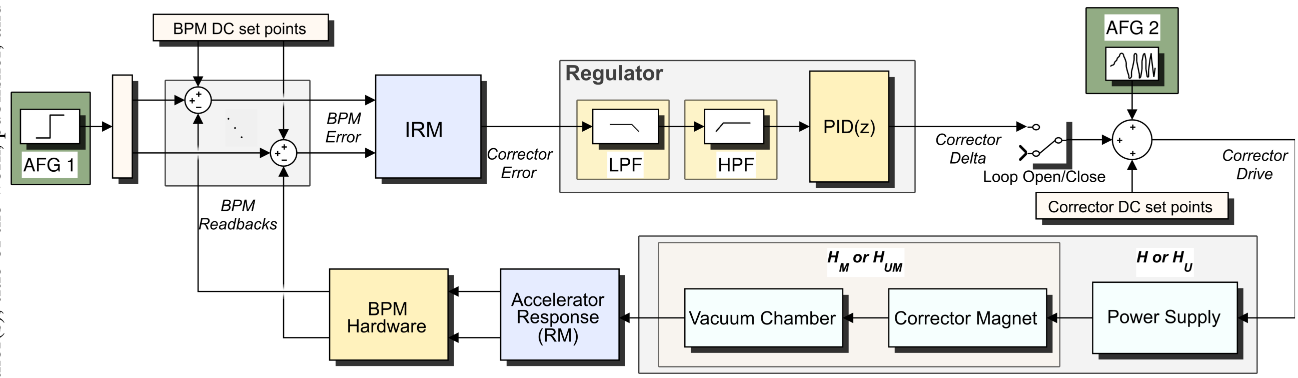

Figure 1: Closed loop layout of Fast Orbit FeedBack System dynamics.

vertical plane. It could be from synchrotron tune frequency. Model dynamics could not simulate this effect.

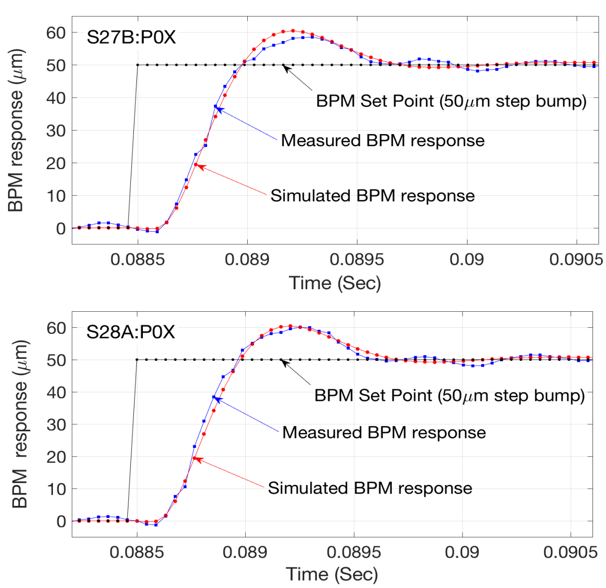

Figure 2: Simulated step responses compared with measurements in horizontal plane

Dynamic Performance Analysis

Closed loop unity-gain bandwidth is used as dynamic performance measure. Input for this measurement is a unit amplitude sine sweep signal applied from AFG 2, measured output is the *Corrector Drive* signal. Attenuation response is the FFT magnitude of corrector drive signal, it's 0 dB crossing frequency is the closed-loop bandwidth. We studied the effects of K_i gain and process delay on closed loop bandwidth, results are shown in Fig. 3. For a closer look of the crossover region, we present attenuation responses between 200 Hz – 5 kHz. With an increase in K_i, bandwidth and maximum amplification are increased. When extra delay is added, bandwidth is decreased and maximum amplification is increased. Also model attenuation responses are compared against the measurements. It can be seen that our model reasonably matches the prototype feedback system dynamics.

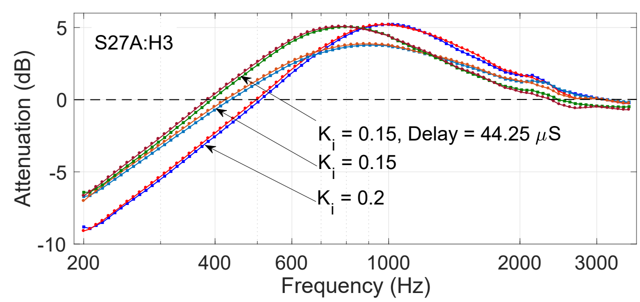

Figure 3: Measured vs Model closed loop attenuation with different latencies and K_i values.

APS-U Performance Prediction

Our objective is to approximate the closed loop performance of the system with APS-U corrector prototype. This process starts with predicting open loop dynamic model $H_U[z]$ for APS-U FOFB system.

$$H_U[z] = H_1[z] \cdot H_{UM}[z] \tag{2}$$

$H_1[z]$ is given in Eq. (1). Transfer function of the prototype fast corrector magnet with vacuum chamber $H_{UM}[z]$, is estimated using dipole frequency data of the MBA prototype corrector.

$$H_{UM}[z] = \frac{-0.94(1+2.93z^{-1})(1+0.43z^{-1})}{(1+0.99z^{-1})(1-0.29z^{-1})(1+0.09z^{-1})} \tag{3}$$

With $H_U[z]$ as the open loop model we simulated closed loop performance. K_i is adjusted to obtain the same maximum amplification factor at high frequencies. Comparison between the closed loop attenuation with present corrector and with prototype magnet model is shown in Fig. 4.

Note: Before directly using the model for testing optimal control methodologies it is essential to understand how effective the model can be when used for model based control design. Since digital PID controller is already implemented on the prototype DSP controller, we decided to design stabilizing PID gains using a model based design algorithm and validate the predicted performance.

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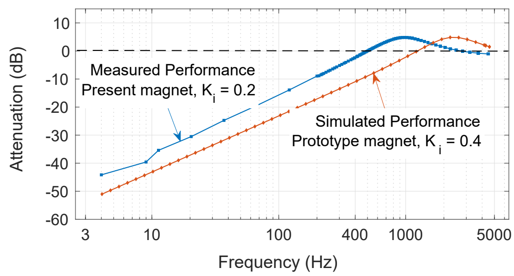

Figure 4: Measured attenuation with present corrector compared to APS-U prototype model response.

MODEL BASED CONTROLLER DESIGN

Model based design algorithm presented in [4] is used to design PID controllers for prototype orbit feedback system. This method uses the Tchebyshev representation of a discrete time transfer function and some results on root counting with respect to the unit circle. The controller transfer function $C[z]$ with proportional (K_p), integral (K_i), derivative (K_d) gains, and sampling time (T_s) is given by,

$$C[z] = K_p + K_i T_s \cdot \frac{z}{z-1} + \frac{K_d}{T_s} \cdot \frac{z-1}{z} \quad (4)$$

Closed loop system responses are simulated with designed PID gains $hPID1$ and $hPID2$. The predicted performance is validated against measurements, horizontal results are shown in Fig. 5 (got similar results in vertical plane).

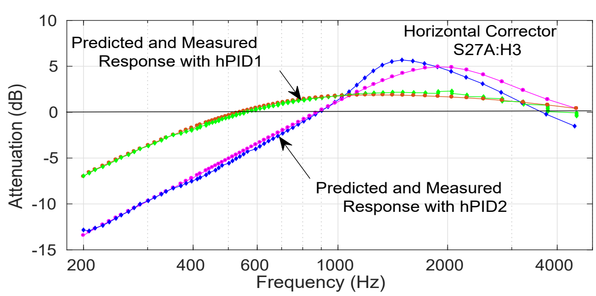

Figure 5: Design Performance Validation.

Better Performance with Designed Controllers

Integral controller can only increase bandwidth by increasing K_i. But it also amplifies some disturbances. The maximum permissible K_i gives 610 Hz closed loop bandwidth and amplification up to 9 dB. With PID controllers designed using the model we gained flexibility to increase the bandwidth further with less amplification. Measured attenuation and orbit motion in both cases are compared in Fig. 6. With designed controller $hPID2$ we got 890 Hz closed loop bandwidth and amplification up to 5.2 dB. Orbit motion up to 1 kHz is comparable to integral controller.

Using Modern Control Theory in FOFB Design

From Fig. 6, we can see that though the closed loop performance with designed controller is better with in 1 kHz in the higher frequency region it is not satisfactory. Control design algorithms that focus just on closed loop stability requirements doesn't offer means to tailor attenuation and rms motion as desired. Modern control theory provides much suitable basis to approach this issue. Control design norms applicable to beam stability design are weight function specifications on *Sensitivity* $S(j\omega)$ and *Complimentary Sensitivity* $T(j\omega)$ functions. For unity feedback closed-loop system with plant $H(j\omega)$ and controller $K(j\omega)$ we have,

$$S(j\omega) = \frac{1}{1 + H(j\omega)K(j\omega)} \quad (5)$$

$$T(j\omega) = \frac{H(j\omega)K(j\omega)}{1 + H(j\omega)K(j\omega)} \quad (6)$$

Magnitude of $S(j\omega)$ is closed loop attenuation. RMS noise response of $T(j\omega)$ is orbit motion. We intend to start our investigation with this framework. First step is to define weight functions $W_S(j\omega)$ and $W_T(j\omega)$. Then the controller $K(j\omega)$ has to be designed such that,

$$\begin{aligned} \|S(j\omega)\| &\leq \|W_S(j\omega)\|^{-1}, \\ \|T(j\omega)\| &\leq \|W_T(j\omega)\|^{-1}. \end{aligned}$$

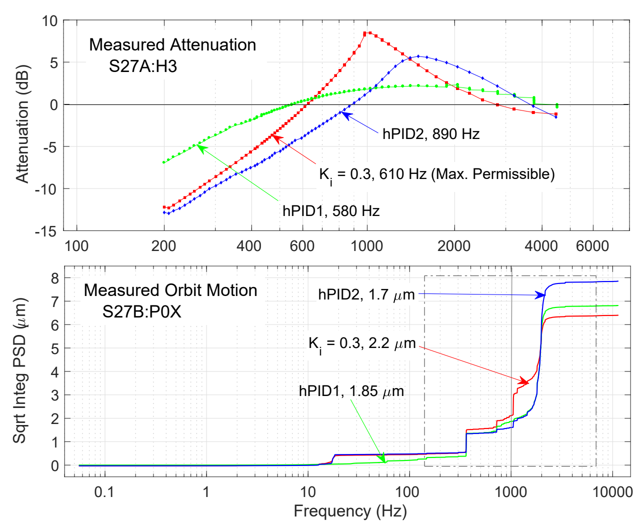

Figure 6: Measured attenuation and orbit motion comparison between designed PID controller and optimal K_i.

CONCLUSIONS

Closed loop modeling and time domain validation of FOFB system for APS-U using the estimated open loop dynamics is summarized. Dynamic performance of prototype feedback system with APS-U 8 pole corrector prototype is predicted. Closed loop attenuation responses with different latencies are measured and compared with simulation results. Model simulation results are in good agreement with the step response and attenuation measurements. Stabilizing PID gains are designed using a model based design algorithm and the predicted performance is validated. Achieved better performance with designed PID gains compared to present integral control. The next step is to use our model to test new methodologies. Also, we plan on refining the model as per the requirements in future.

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