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# MODELING THE FAST ORBIT FEEDBACK CONTROL SYSTEM FOR APS UPGRADE*

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*Abstract*

The expected beam sizes for APS Upgrade (APS-U) are in the order of 4 microns for both planes. Orbit stabilization to 10% of the beam size with such small cross-sections requires pushing the state of the art in Fast Orbit Feedback (FOFB) control, both in the spatial domain and in dynamical performance; the latter being the subject of this paper. In this paper, we begin to study possible performance benefits of moving beyond the classic PID regulator to more sophisticated methods in control theory that take advantage of a-priori knowledge of orbit motion spectra and system non-linearities. A reliable model is required for this process. Before developing a predictive model for the APS Upgrade, the system identification methodology is tested and validated against the present APS storage ring. This paper presents the system identification process, measurement results, and discusses model validation.

## INTRODUCTION

The current APS real-time orbit feedback system has been in routine operation for more than 20 years and was the first digital truly global orbit feedback system to be implemented at a light-source. A distributed array of DSPs compute orbit corrections at 1.6 kHz using a matrix of 160 bpms x 38 correctors per plane. Unity-gain bandwidth is 60-80 Hz [1]. The regulator uses just the integral term of a classical PID, and is tuned for minimum residual broad-band rms orbit motion. A higher $K_i$ than optimal gives better attenuation at lower frequencies but comes at the expense of amplifying residual motion at higher frequencies. The optimum value of $K_i$ therefore depends on the spectral content of the orbit motion. A new orbit feedback system is under development for the APS Upgrade, where the smaller beam size drives orbit stability requirements that are considerably more stringent than the present APS. The new orbit feedback system will use a distributed array of DSPs to compute orbit corrections at 22.6 kHz (12x faster than the present system) and using a matrix of 560 bpms and 160 correctors. The target unity-gain bandwidth is 1 kHz. We need to study the possible performance benefits of moving beyond classic PID regulator and investigate different controller design methods in advanced control theory that are applicable to electron beam stabilization. A reliable model is required for this process since most of the advanced control algorithms are model based. We start this investigation by first modeling the FOFB system. Prototype feedback controllers, and fast corrector power supplies developed under R&D for APS-U have been integrated in prototype feedback system 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.

Main tasks involved in the system modeling are: to develop a open loop system model, to create a simulation model of the DSP controller, and use them to implement a real time simulation setup that represents FOFB control system for APS-U. The layout of the FOFB system in closed loop is shown in Fig. 1. The open loop dynamics are represented by the process transfer function from corrector power supply set point to BPM read backs. Let $H[z]$ be the transfer function of open loop system with present corrector magnet. We assume,

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

where $H_M[z]$ is the transfer function of the present corrector magnet, and rest of the dynamics are represented by the transfer function $H_1[z]$. Then, the predicted open loop dynamics of the FOFB system for APS-U can be represented by,

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

where, $H_{UM}[z]$ is the transfer function of the prototype fast corrector magnet. Developing the simulink model of the DSP controller is the next step in the process. BPM readbacks are the input to this model and the outputs are the corrector set points to power supply.

In this work, Matlab System Idendification Toolbox is used for model estimation. Data pre-processing, model validation are done in Matlab and Simulink environment.

## SYSTEM IDENTIFICATION PROCEDURE

In this modeling we assume the FOFB system in open loop is linear time-invariant. The model application in our case is to use it for control design, so having accurate model around the crossover frequency is important.

### Data Collection

The modelling process starts with collecting the data required for matlab system identification tool. Experiments are conducted to measure open loop time and frequency response data. For open loop measurements, input is the corrector setpoint to power system and output measured is BPM readbacks. Time response is measured with an unit step signal input at corrector drive. The measured step response data is preprocessed by smoothing and removing the zero offset. For open loop frequency response measurements, sine sweep signal with step changes in frequency

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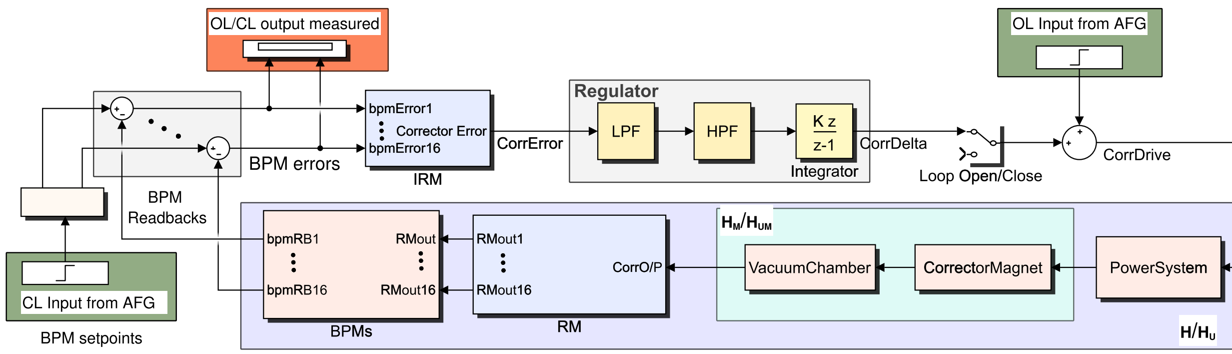


Figure 1: Fast Orbit FeedBack System layout for a single Fast Corrector.

ranging from 15 Hz - 6 kHz is used as input. The measured sine sweep response is detrended to zero to remove the offset and smoothed. This data is then used to calculate the magnitude and phase at each discrete frequency. In this paper we present the modeling results of the Single Input Single Output (SISO) transfer function from S27AH3 fast corrector to S27AP0 BPM. The measured step response data is shown in Fig. 2, and the frequency response data is shown in Fig. 3.

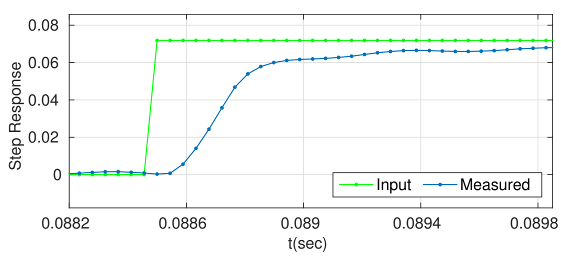


Figure 2: Measured step response.

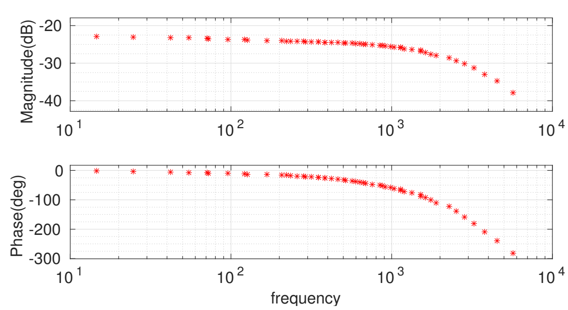


Figure 3: Measured frequency response.

From the step response data we have the information about the stationary gain and time delay of the system. In our case the delay is approximately 1-tick of the sample time. From the calculated frequency response data we can find possible relative degree (difference between number of poles and zeros) of the system transfer function. It can be calculated from the high frequency slope of frequency response magnitude. For this data the possible relative degree is either one or two.

### *Model Estimation*

The next step in the system identification process is model estimation. Measured step/frequency response data and time delay are used as the input to the transfer function estimation. The combination of line search algorithms available in Matlab System Identification Tool are used to fit measured data in to the selected transfer function structure. Open-loop beam-based measurements give the observed change in the orbit to an applied change in the corrector power supply drive, and hence they include the dynamics of the power supply, magnet, vacuum chamber and bpms. The estimated model should therefore reflect the convolution of the transfer functions of the individual components. Based on a-priori knowledge of the physical components, the following assumptions were made in order to make an initial estimate of the order of the transfer function:

- From bench measurements, the transfer function of the corrector power supply is assumed to be second-order with complex poles located around 10 kHz.
- The corrector magnets surround an Inconel bellows, and eddy-current effects are assumed to be fast compared with the magnet response. Although eddy-current effects are not fully-representable in an LTI model, we assume an approximation of a small delay plus a high-frequency roll-off of at least one pole.
- The magnet response is assumed to start rolling off in the range of a few 100's of Hz, and can be approximated by two or more poles (at least one pole to account for magnet core losses).

Transfer function structures with different orders (4 and above), and relative degree one or two are considered for estimation. Two ways to incorporate the delay are explored. One, measured data with delay is fit in to a single transfer function. Other, delay is considered as a separate component. Transfer function models are estimated using different choices discussed above. Six pole, four zero transfer function model $H[z]$ shown in Eq. (3) looks to be a good fit with measured data. In this model, delay is not separated from the transfer function.

$$H[z] = C_1[z] \cdot C_2[z] \cdot C_3[z] \tag{3}$$

where,

$$C_1[z] \quad = \quad 0.939\frac{1 - 1.536z^{-1} + 0.861z^{-2}}{1 - 1.583z^{-1} + 0.889z^{-2}}$$

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$$C_2[z] = \frac{-0.120(1-2.880z^{-1})}{(1+0.489z^{-1})(1-0.522z^{-1})(1-0.681z^{-1})}$$

$$C_3[z] = 0.855\frac{1-0.974z^{-1}}{1-0.978z^{-1}}$$

By inspecting pole-zero locations, $H[z]$ is futher seperated into three transfer functions in series. Both $C_1[z]$ and $C_3[z]$ has gains close to unity, their step responses are shown in Fig. 4. $C_1[z]$ shows expected dynamics of the power supply i.e., it has 2 poles, and has fast rise time with considerable settling time. $C_3[z]$ has critically damped step response, is close to expected dynamics of the vacuum chamber. We then consider $C_2[z]$ represents dynamics of fast corrector magnet. Simulated step responses of the magnet, magnet with vacuum chamber, and complete open loop dynamics are shown in Fig. 5.

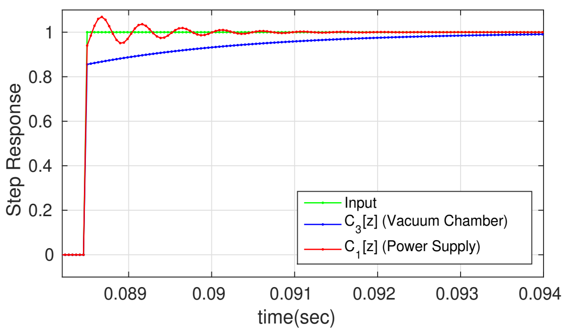


Figure 4: Step Responses of $C_1$ and $C_3$

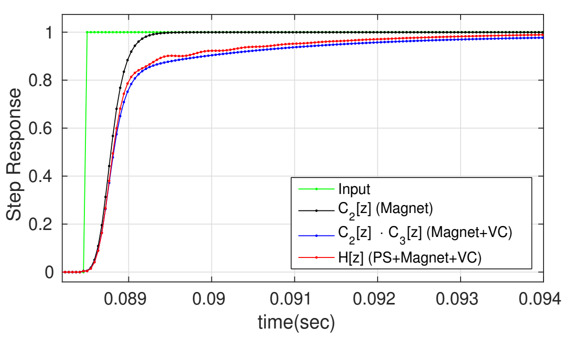


Figure 5: Step Responses of $C_2$, $C_2 \cdot C_3$, and $H$

## MODEL VALIDATION

### *Open loop system model*

The estimated model is validated by checking the consistency of the simulated model response with the measured data in open loop and in closed loop (with a known stabilizing controller). Figure 6 shows the comparison of the simulated and measured open loop step responses.

Simulink model of closed loop system is implemented using the estimated model and a single integrator. Step input is given at BPM set point. Measured and simulated corrector drive signal responses are compared. Figure 7 shows the comparison of the simulated and measured closed loop step responses for $K_i = 0.2$. The model reasonably represents open loop and closed loop behavior of the present system. We plan on refining it as per the requirements in future.

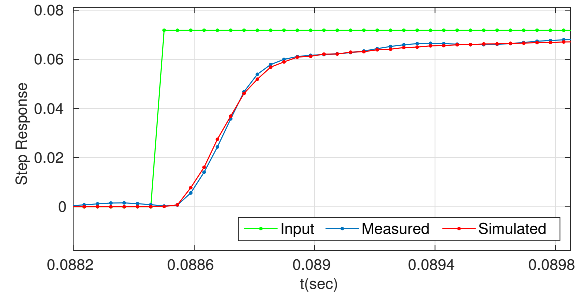


Figure 6: Measured vs Model open loop step response.

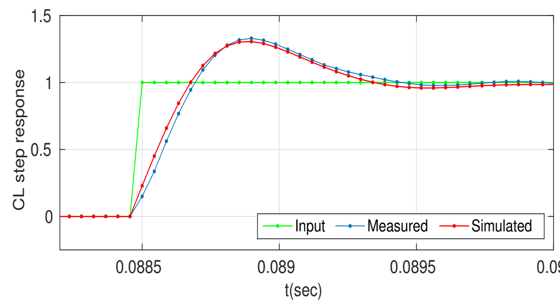


Figure 7: Measured vs Model closed loop step response, $K_i = 0.2$.

### *Simulink model for DSP controller*

The controller schematic is modeled in Matlab Simulink and is implemented on DSP eval board using the same algorithms for each element. Significant elements of the controller model are IRM, and the regulator with LPF, HPF and PID controller. The output of the controller for different operation testcases are compared to validate that the Simulink model and the DSP implementation are equivalent.

## CONCLUSIONS

System modeling plan to develop a FOFB system predictive model for APS-U is summarized. SISO transfer function model representing the single fast corrector to single BPM dynamics, is estimated using Matlab System Identification Tools. Estimated model response is validated against the measured open loop and closed loop step response data. At present we are assuming all the correctors will have the same dynamics. The next step is to model the relative differences in dynamics of different correctors.

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