A Unified Approach to Global and Local Beam Position Feedback*

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Abstract

The Advanced Photon Source (APS) will implement both global and local beam position feedback systems to stabilize the particle and X-ray beams for the storage ring. The global feedback system uses 40 BPMs and 40 correctors per plane. Singular value decomposition (SVD) of the response matrix is used for closed orbit correction. The local feedback system uses two X-ray BPMs, two rf BPMs, and the four magnet local bump to control the angle and displacement of the X-ray beam from a bending magnet or an insertion device. Both the global and local feedback systems are based on digital signal processing (DSP) running at 4-kHz sampling rate with a proportional, integral, and derivative (PID) control algorithm. In this scheme, the global feedback system absorbs the local bump closure error and the local feedback systems compensate for the effect of global feedback on the local beamlines. The required data sharing between the global and local feedback systems is done through the fiber-optically networked reflective memory.

1. INTRODUCTION

The Advanced Photon Source (APS) is one of the third-generation synchrotron light sources which are characterized by low emittance of the charged particle beams and high brightness of the photon beams radiated from insertion devices. In order to achieve the stringent transverse X-ray beam position stability required by the current user community, we are developing an extensive beam position feedback systems with the correction bandwidth approaching 100 Hz. [1-3]

The APS storage ring has 360 rf beam position monitors (BPMs) and 318 corrector magnets distributed around the storage ring, miniature BPMs for insertion device beamlines, and photon beam position monitors in the front end of X-ray beamlines for global and local orbit correction. The real-time (AC) feedback systems, which are the main focus of this work, will use a subset of these to counteract the effect of various vibration sources, including the ground vibration, mechanical vibration of the accelerator subcomponents, thermal effect, and so forth.

The feedback systems can be largely divided into the global and local feedback systems according to the scope of correction. The global feedback system uses 40 rf BPMs and 40 corrector magnets distributed equally in 40 sectors. The

relating the angle and displacement of the photon beam and the two bump strengths.

The remaining component matrix $R_{\text{inv,lg}}$ is determined such that the effect of the global correctors on the local feedback is canceled by considering the global and local feedback systems as a single, unified feedback system. This can be done by setting

$$R_{\text{inv,lg}} = -R_{\text{inv}} R_{lg} R_{\text{inv}}.$$  \hspace{1cm} (2)

The physical interpretation of Eq. (2) can be given as follows. $R_{\text{inv}}$ is the response of the global correctors to global orbit perturbation, $R_{lg}$ is the local orbit perturbation due to global correctors, and $R_{\text{inv}}$ is the response of the local correctors to local orbit perturbation. The matrix product $R_{\text{inv}} R_{lg} R_{\text{inv}}$ is then the response of the local correctors to global orbit perturbation and $R_{\text{inv,lg}}$ in Eq. (2) compensates for the action of the global feedback on the local orbits, resulting in maximum orbit correction efficiency.

### 2.3 Feedback System Dynamics

The schematic diagram of the feedback system is shown in Fig. 3. We assume a digital feedback system and will analyze it using the technique of Z-transform.\[4\] The sampling time is $T$ and the sampling frequency $F_s$ is equal to $1/T$. $\{s_n\}$ and $\{y_n\}$ are the discrete sequences of vectors representing the reference and measured orbits. The gain matrix $G$ includes the feedback controller and a bandwidth-limiting filter, and the matrix $H$ represents the BPM bandwidth. The external perturbation is given by $\{w_n\}$.

The difference equation describing the response of the feedback system in Fig. 3 is given by

$$y_{n+1} = H \cdot R \cdot R_{\text{inv}} \cdot G \cdot (s_n - y_n) + w_{n+1}. \hspace{1cm} (3)$$

Applying the Z-transform to Eq. (3), we obtain

$$Y(z) = \left\{ 1 - F(z) \frac{1}{H(z)} \right\} \cdot S(z) + F(z) \cdot W(z) \hspace{1cm} (4)$$

where

$$F(z) = \frac{1}{1 + H(z) \cdot R \cdot R_{\text{inv}} \cdot G(z) \cdot z^{-1} H(z)}. \hspace{1cm} (5)$$

$Y(z)$ is the Z-transform of $\{y_n\}$, $W(z)$ is the Z-transform of $\{w_n\}$ and so forth. The expression $1/\cdot(\cdot)$ denotes the inverse matrix. The matrix $F(z)$ is the noise-filter matrix and with the substitution $z = \exp(-\mathbf{i} \omega T)$, we can obtain the frequency
response of the feedback system. The last term in Eq. (4) represents the residue of the perturbation in the orbit with feedback. Using Eq. (2) and assuming $R_R_{	ext{inv}} = 1$, it can be shown that the matrix product $R_R_{	ext{inv}}$ is given by

$$R_R_{	ext{inv}} = R_R \cdot R_R_{\text{inv}} + I_I$$

in the ideal case of no local bump closure error. The operator $\oplus$ combines two matrices as depicted in Fig. 4.

![Fig. 4: The matrix combination operator $\oplus$.](image)

Now, putting

$$G(z) = G_g(z) 1_g \oplus G_l(z) 1_l \quad \text{and} \quad H(z) = H_g(z) 1_g \oplus H_l(z) 1_l$$

we obtain

$$F(z) = U \cdot F_g(z)U^T \oplus F_l(z),$$

where $U$ is the unitary global BPM transform matrix derived from SVD, and $F_g(z)$ and $F_l(z)$ are diagonal. Equation (8) indicates that there exists a coordinate transformation that decouples the feedback channels, and single-channel feedback theory can be applied to each channel.

Using the relation $U^T U = U^T H = I_I$, we obtain from Eqs. (4) and (5) the diagonal elements of $F_g(z)$ as

$$F_{g,\text{coupled}}(z) = \frac{H_g(z)}{1 + H_g(z)G_g(z)z^{-1}} \quad \text{and} \quad F_{g,\text{decoupled}}(z) = 0$$

and similarly for $F_l(z)$. The noise filter matrix for the BPMs can be obtained from Eqs. (8) and (9). The expression for the coupled modes is identical to that of a single-channel feedback system.[3] The PID controller function $G(z)$ is given by

$$G(z) = \frac{K_p + \frac{K_i}{1 - z^{-1}} + K_d(1 - z^{-1})}{1}$$

where $K_p$, $K_i$, and $K_d$ are the proportional, integral, and derivative controller gains, respectively. When $K_i$ is finite, the open loop DC gain is infinite, and therefore, the long-term drift can be completely corrected.

3. ANALYSIS OF THE APS FEEDBACK SYSTEM

In this section, we will discuss the results of simulation on the APS beam position feedback system with 20 local feedback systems. Due to the relatively thick (1/2") aluminum vacuum chamber at the location of local corrector magnets, a strong eddy current is induced in the vacuum chamber. This causes attenuation and phase delay of the applied magnetic field and generates a strong quadrupole magnetic field (13% per cm at 20Hz) inside the chamber. This leads to local bump closure error when the particle beam is at a significant distance from the vacuum chamber center. The magnet field error due to calibration error and saturation adds to this effect.

Figure 5 shows simulated results comparing the cases when the global and local feedback systems are coupled ($R_{\text{inv},g} = 0$) and decoupled ($R_{\text{inv},g} = 1$). It also shows the attenuation of noise by the feedback system. Random field error less than 2% and orbit deviation less than 3 mm were assumed with the vacuum chamber eddy current taken into account. The correction efficiency is shown in terms of the local corrector load (mrad/mm) necessary to correct a given orbit perturbation of global SVD eigenmodes. Decoupling the global and local feedback systems results in significant improvement in the correction efficiency beyond 10 Hz.

![Fig. 5: Improvement of local orbit correction efficiency for the decoupled feedback system in correcting global SVD eigenmodes. Random field error less than 2% and orbit deviation less than 3 mm were assumed with the vacuum chamber eddy current taken into account.](image)

5. REFERENCES


