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Closed Orbit Feedback with Digital Signal Processing*

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Abstract

The closed orbit feedback experiment conducted on the SPEAR using the singular value decomposition (SVD) technique and digital signal processing (DSP) is presented. The beam response matrix, defined as beam motion at beam position monitor (BPM) locations per unit kick by corrector magnets, was measured and then analyzed using SVD. Ten BPMs, sixteen correctors, and the eight largest SVD eigenvalues were used for closed orbit correction. The maximum sampling frequency for the closed loop feedback was measured at 37 Hz. Using the proportional and integral (PI) control algorithm with the gains $K_P = 3$ and $K_I = 0.05$ and the open-loop bandwidth corresponding to 1% of the sampling frequency, a correction bandwidth (-3 dB) of approximately 0.8 Hz was achieved. Time domain measurements showed that the response time of the closed loop feedback system for 1/e decay was approximately 0.25 second. This result implies ≈100 Hz correction bandwidth for the planned beam position feedback system for the Advanced Photon Source storage ring with the projected 4-kHz sampling frequency.

1. INTRODUCTION

One of the primary requirements from today's synchrotron light source users is the stringent transverse stability of the X-ray beam emitted from the bending magnets and insertion devices. Correction bandwidth of approximately 100 Hz and long-term drift of less than 10% of the transverse beam size will be routinely expected from the third-generation synchrotron light sources which are characterized by low emittance of the charged particle beam and high brightness of the photon beam.

Sources of beam motion includes ground vibration, mechanical vibration of the accelerator subcomponents, thermal effects, and so forth. In order to counteract the effect of these sources, feedback systems that comprise the beam position monitors (BPMs), corrector magnets, and processing units are typically used.

The beam position feedback systems can largely be divided into global and local feedback systems according to the extent of correction, and DC and AC feedback systems according to the bandwidth of correction.

In this paper, we will present the results of global AC beam position feedback experiments conducted on SPEAR at the Stanford Synchrotron Radiation Laboratory (SSRL). The proportional and integral (PI) control algorithm was used, and the technique of singular value decomposition (SVD) was used to invert the response matrix. A dedicated VME-based digital signal processor (DSP) was used to compute the corrector strength. Two VME CPUs and one ADC/DAC board were used to digitize the BPM signal and to control the correctors.

The rest of this paper will consist of a theoretical review of the global beam position feedback with DSP in Section 2, description of the experimental setup in Section 3, and presentation of the results in Section 4.

2. THEORY

Let us consider a global beam position feedback system based on DSP with M BPMs and N correctors. The sampling time is T and its reciprocal is the sampling frequency F_s. The schematic diagram of the system is shown in Fig. 1. $\{s_n\}$ and $\{y_n\}$ are the discrete sequences of M-element vectors representing the reference and measured orbits. The gain matrix **G** includes the feedback controller and a bandwidth-limiting filter. The matrix **H** represents the BPM transfer function. The external perturbation is given by $\{w_n\}$.

The response matrix **R** is defined as the beam motion at BPM locations per unit kick by corrector magnets. The inverse response matrix $\mathbf{R}_{inv}$ is the matrix used to obtain the corrector strength vector $\Delta\boldsymbol{\theta}$ to correct the orbit error Δy, that is,

$$\Delta\boldsymbol{\theta} = \mathbf{R}_{inv} \cdot \Delta \mathbf{y} . \tag{1}$$

In this work, $\mathbf{R}_{inv}$ was obtained using the SVD of the response matrix.[1-4] The details of the SVD technique can be found in the references and will not be discussed in this paper.

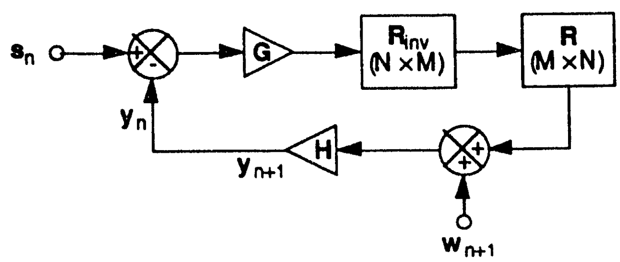

Fig. 1: The schematic diagram for the global beam position feedback system.

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DISCLAIMER

Let us for simplicity take an arbitrary reference orbit and set $s_n = 0$ for all n. Then the effect of the perturbation $\{w_n\}$ on the global orbit in the z-domain can be given as[5,6]

$$\mathbf{Y}(z) = \mathbf{F}(z)\cdot\mathbf{W}(z) \tag{3}$$

where

$$\mathbf{F}(z) = \frac{1}{1 + \mathbf{H}(z)\cdot\mathbf{R}\cdot\mathbf{R}_{inv}\cdot\mathbf{G}(z)z^{-1}}\,\mathbf{H}(z). \tag{4}$$

$\mathbf{Y}(z)$ is the Z-transform of $\{\mathbf{y}_n\}$, $\mathbf{W}(z)$ is the Z-transform of $\{\mathbf{w}_n\}$, and so forth. The expression 1/(..) denotes the inverse matrix. The matrix $\mathbf{F}(z)$ is the noise-filter matrix and with the substitution $z = \exp(-i\omega T)$, we can obtain the frequency response of the feedback system.

Using the SVD method, if the diagonal matrices $\mathbf{G}(z)$ and $\mathbf{H}(z)$ have identical elements along the axis, $\mathbf{F}(z)$ can be written as

$$\mathbf{F}(z) = \mathbf{U}\cdot\mathbf{F}_{SVD}(z)\cdot\mathbf{U}^T \tag{5}$$

where $\mathbf{U}$ is the unitary BPM transform matrix derived from SVD, and $\mathbf{F}_{SVD}(z)$ is a diagonal matrix. Equation (5) 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 $\mathbf{U}\cdot\mathbf{U}^T = \mathbf{U}^T\cdot\mathbf{U} = \mathbf{1}$, we obtain from Eqs. (4) and (5) the diagonal elements of $\mathbf{F}_{SVD}(z)$ as

$$F_{SVD,ii}(z) = \begin{cases} \dfrac{H(z)}{1 + H(z)G(z)z^{-1}} & \text{coupled modes} \\ 0 & \text{decoupled modes.} \end{cases} \tag{6}$$

The noise filter matrix for the BPMs can be obtained from Eqs. (5) and (6). The expression for the coupled modes is identical to that of a single-channel feedback system.[7] The PID controller function G(z) is given by

$$G(z) = K_P + \frac{K_I}{1 - z^{-1}} + K_D(1 - z^{-1}), \tag{7}$$

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. EXPERIMENTAL SETUP

Figure 2 shows the schematic of the experimental setup with ten BPMs and sixteen correctors. The BPM multiplexer scans a total of forty striplines and relays stripline ID and signal to two ADCs in the VME crates. The VME CPUs compute the beam positions from these data and write them to the reflective memory. The DSP calculates the corrector strength from the orbit error and writes the data to the reflective memory, which are read by the VME CPUs and written to the DACs to control the corrector power supplies.

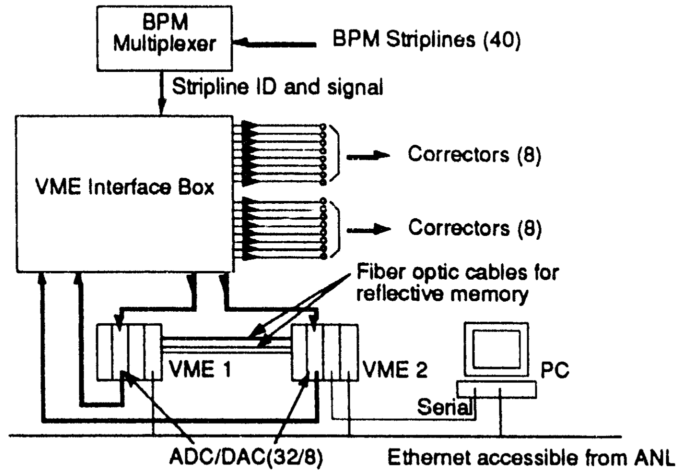

Fig. 2: Schematic of the setup for global AC beam position feedback experiments on SPEAR, SSRL.

Selection of the BPMs and correctors were made considering the following factors: 1) the maximum number of channels on the DAC for corrector control was sixteen, 2) the singularity parameter $\varepsilon_m = w_{min}/w_{max}$ must be maximized for efficient feedback, 3) optimize the number of BPMs for the highest possible sampling frequency and orbit correction accuracy. From these considerations, ten BPMs and sixteen correctors were selected for closed orbit correction as listed in Table 1. The β and ψ are model values.

Table 1: List of the BPMs and correctors used for feedback.

BPM	ψ/2π	β(m)	Corrector	ψ/2π	β(m)
15S16	1.0235	2.7698	15QDT	1.3009	32.5586
14S15	1.3963	2.4643	14QDT	1.6590	35.4755
13S14	1.9572	2.3970	13QF2T	1.9900	3.5207
12S13B	2.1319	2.7277	13QF1T	2.1025	3.8711
11S12	2.5042	2.4998	12QDT	2.4101	32.8681
10S11	2.8061	7.3896	12QF1T	2.4717	3.4619
8S9	3.8777	7.3895	11QFBT	2.7107	3.7635
6S7	4.3701	2.3931	11QFAT	2.7934	7.8618
5S6	4.7270	2.3903	8QF1T	3.9733	3.7637
2S3	5.8358	2.3542	7QF2T	4.2122	3.4617
			7QF1T	4.3366	3.3432
			6QF2T	4.5814	3.8709
			6QF1T	4.6939	3.5204
			5QF2T	4.9651	3.3929
			5QF1T	5.0813	3.8079
			4QF1T	5.4461	3.3486

For beam position measurement, the signals from BPM striplines were multiplexed and processed by an analog circuit and then digitized by an ADC with 12-bit resolution and ±5V full scale. The beam position was then calculated in dimensionless units as:

$$x = 65{,}536 \times \frac{V_1 - V_2 - V_3 + V_4}{V_1 + V_2 + V_3 + V_4} \tag{8}$$

and similarly for y. The constant 65,536 was multiplied in order to convert the signal ratio to an integer.

The corrector power supply was controlled through a DAC with 12-bit resolution and ±5V full scale corresponding to ±60A current range. The response matrix was measured in dimensionless units as the ratio of the beam motion and corrector strength changes. The response matrix is not singular and the eigenvalues ranged from 9.152 to 0.242 giving $\varepsilon_m = w_{min}/w_{max} = 0.0264$.

Signal processing for feedback is distributed among three processors, two VME CPUs (Motorola 68040), and a dedicated digital signal processor (Texas Instruments' TMS320C30). The beam positions are obtained independently by the VME CPUs through two ADCs for redundancy. The average of the two sets of data is used to calculate the global orbit error. Two reflective memories, each in a VME crate, were used for data sharing between the two VME crates. Data written to one reflective memory are automatically duplicated in all others in the chain. Using this feature, the corrector strength calculated by the DSP is written to the reflective memory and the VME CPU in the other crate can read the data duplicated in the reflective memory in its crate.

4. RESULTS

The performance of the feedback system was measured in both the time and frequency domains. For the time domain measurement, a step impulse of 25 A was applied to the corrector 2QFAT to generate global orbit distortion. The electron energy was 2.27 GeV and a beam position shift of approximately 1.6 mm was observed at BPM 8S9 with the feedback turned off as shown in Fig. 3(a). With the feedback turned on, the initial beam position shift decayed exponentially and the orbit was restored to the reference. Figure 3(a) shows that the response time of the closed loop feedback system for 1/e decay was approximately 0.25 second.

The frequency response measurement of the feedback system was made by perturbing the orbit at the selected frequencies 0.01, 0.05, 0.1, 0.5, 1, 2, and 5 Hz with feedback turned on and off, and the ratio of the amplitudes was calculated. Figure 3(b) shows the result. The sampling frequency was measured at 37 Hz and the open loop bandwidth was set at 1% of the sampling frequency, that is, 0.37 Hz. The feedback controller gains were $K_P = 3$, $K_I = 0.05$, and $K_D = 0$, with which a closed loop bandwidth of approximately 1 Hz can be expected for -3dB noise rejection. This is in good agreement with the result shown in Fig. 3(b). For the APS beam position feedback systems, which will run at the projected sampling frequency of 4 kHz, this result implies that the orbit correction bandwidth will be approximately 100 Hz.

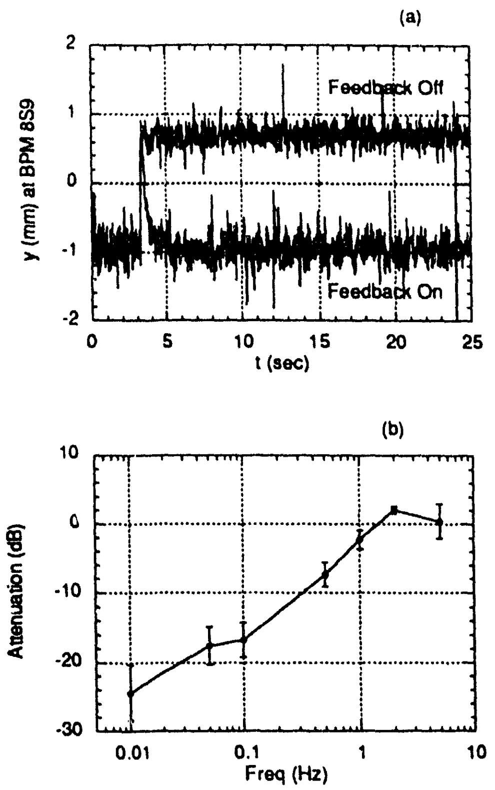

Fig. 3: Result of global orbit feedback on SPEAR, SSRL in (a) time domain and (b) frequency domain. The parameters used were: $K_P = 3$, $K_I = 0.05$, $K_D = 0$, $F_s = 37$ Hz, and $f_b = 0.37$ Hz.

5. REFERENCES

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