A STATE VARIABLE APPROACH TO THE BESSY II LOCAL BEAM-POSITION-FEEDBACK SYSTEM*

J. D. GILPATRICK**, S. KHAN, D. KRÄMER, BESSY II, Berlin, Germany

ABSTRACT

At the BESSY II facility, stability of the electron beam position and angle near insertion devices (IDs) is of utmost importance. Disturbances due to ground motion could result in unwanted broad-bandwidth beam-jitter which decreases the electron (and resultant photon) beam's effective brightness. Therefore, feedback techniques must be used. Operating over a frequency range of <1- to >100-Hz, a local feedback system will correct these beam-trajectory errors using the four bumps around IDs. This paper reviews how the state-variable feedback approach can be applied to real-time correction of these beam position and angle errors. A frequency-domain solution showing beam jitter reduction is presented. Finally, this paper reports results of a beam-feedback test at BESSY I.

1 INTRODUCTION

The BESSY II facility [1], presently being constructed in Berlin, will provide synchrotron light for fundamental and applied research. Synchrotron light is produced in 32 dipoles and 14 IDs distributed around the 1700-MeV, electron-beam storage ring and transported to various experimental areas. If the stored electron beam trajectory moves rapidly or jitters in an ID, the resulting synchrotron light jitters on the experimental target which reduces its effective-brightness and decreases the photon beams usefulness to users.

To minimize this jitter, two types of beam feedback systems will be implemented. A global feedback system will correct slow closed-orbit variations (i.e., typically <1 Hz) throughout the ring transport. However, much of the beam jitter sources have spectral content >1-Hz. Therefore, faster local-feedback systems will be built to stabilize the beam in individual IDs. The local feedback system should reduce the expected 20-µm beam jitter to 1 µm (10 µm) in the vertical (horizontal) axis with bandwidths of <1 to >100 Hz.

2 BEAM POSITION- AND ANGLE-FEEDBACK SYSTEM

As shown in Fig. 1, the beam position- and angle-feedback system consists of four steering magnets and power supplies, electron-beam position and angle processors, feedback and trajectory transformations, and the electron beam transport. The steering magnets produce four kicks configured so that electron-beam trajectories into the first, $\vec{\mathbf{x}}_1(t)$, and out of the last steering magnet, $\vec{\mathbf{x}}_4(t)$, remain unchanged with or without beam feedback or steering corrections. Stated mathematically using beam transport notation [2],

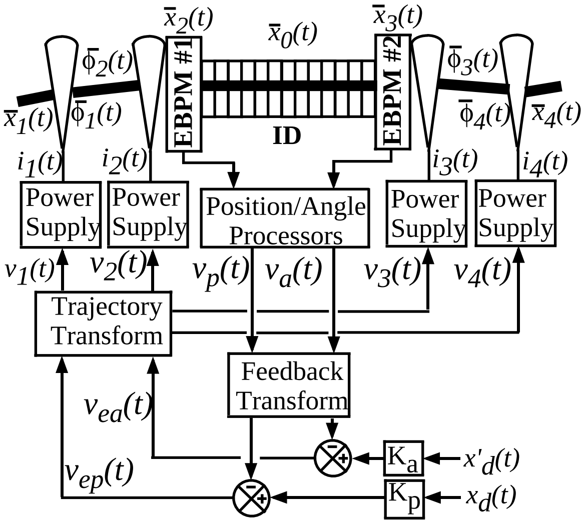

Figure 1: Local beam position- and angle-feedback corrects beam trajectory at the ID center.

$$\mathbf{M}_{14}\vec{\phi}_1(t)+\mathbf{M}_{24}\vec{\phi}_2(t)+\mathbf{M}_{34}\vec{\phi}_3(t)+\vec{\phi}_4(t)=\vec{0} \qquad (1)$$

where the vector $\vec{\phi}_i(t)$ describes the kick produced by corrector i and M_{ij} is the transfer matrix between correctors i and j. Feedback is applied using the first two steerers and the equation

$$\mathbf{M}_{10}\vec{\phi}_1(t)+\mathbf{M}_{20}\vec{\phi}_2(t)=\vec{\mathbf{x}}_0(t) \qquad (2)$$

where $\vec{\mathbf{x}}_{\mathbf{0}}(t)=\left[x_0(t) \quad x'_0(t)\right]^T$ is the vector describing the measured beam trajectory at the ID longitudinal center. This closed bump condition guarantees that the local feedback system inside the bump will not jeopardize the storage ring's closed-orbit stability.

Since the ID should not alter the average beam trajectory, $\vec{\mathbf{x}}_{\mathbf{0}}(t)$ is determined by measuring the electron beam's position before and after the ID. Photon beam position measurements may also be used.

Each magnet's power supply must have sufficient peak power to respond to fast movements of the beam (i.e., the power supply must be capable of supplying high-current slew rates). For the BESSY II steerer-magnet design, an angular kick of 0.4 milliradians is obtainable with 20

---

[*] Funded by the Bundesministerium für Bildung, Wissenschaft, Forschung umd Technologie and by the Land Berlin.

[**] guest scientist from LANL (Los Alamos, NM, USA)

amps flowing in the magnet coils. The coils' inductance and resistance are 0.5 mH and 50 mΩ, respectively. Because the BESSY II beam pipes are very thin (i.e., 2 mm), the steerer magnet fields will be reduced and delayed by only 12% and 8° at 100 Hz, respectively. Therefore, these eddy-current effects are considered negligible and no added transformations are necessary.

The measured and transformed beam trajectory is subtracted from the desired trajectory at the ID center, $\bar{\mathbf{x}}_d(t)$, to form the error trajectory, $\bar{\mathbf{x}}_e(t)$. The trajectory transformation calculates the four steering angular kicks required to maintain closed bump condition. The feedback transformation provides the states or outputs used for the feedback loop(s). The example in this paper uses a simple first order feedback know as proportional feedback. However, by feeding back other order states, the closed-loop system's stability and dynamics may be improved. For example, a second order system can have an integral and a differential order of feedback (i.e., proportional, integral, and differential or PID).

Because there are no position measurements to verify that steerers #3 and #4 have properly steered the beam, $\bar{\mathbf{x}}_4(t)$ may be incorrect if the response of power supplies #3 and #4 do not match #1 and #2. A beam position measurement located just upstream of steerer #4 would partially correct this inadequacy.

3 STATE VARIABLE SOLUTION

The state variable approach uses the multi-order differential equation that describes the beam measurement and steering dynamics. This multi-order differential equation is separated into a series of first order differential equations. The state vector is defined by, but not limited to, each of the first-order differential-equation variables.

Only loop components are included in the feedback system drawn in Fig. 2, therefore, power supplies and steering magnets #3 and #4 are not included. The beam-position processor output-signal, $V_p(s)$, is

$$V_p(s) = X_0(s) K_p \, \alpha / (s+\alpha) \tag{3}$$

where $s = i\omega$, K_p is the position measurements conversion coefficient, and α is the position measurement's low-pass-filter pole. The beam angle measurement has a similar transfer function. The first beam kick, $\Phi_1(s) = V_1(s) K_{ps}(s) K_\phi$, is

$$K_{ps}(s) = \frac{p_s G_I / L_m}{(s+p_s)\big(s+(R_m+R_2)/L_m\big) + p_s G_I R_2 / L_m} \tag{4}$$

where $V_1(s)$ is the power-supply input signal, G_I is the current gain, K_ϕ is the magnets' kick coefficient, p_s is the power supply's pole, L_m and R_m are the magnet coil's inductance and DC resistance, and R_2 is the power supply's voltage-follower resistance. The trajectory transform, $\mathbf{T}$, specifies the coupling between the beam position and angle loops as defined by the closed orbit bump condition.

Modern control-theory notation [3], defines a state vector, $\vec{X}(s)$, and an output vector, $\vec{Y}(s)$, as

$$s\vec{\mathbf{X}}(s) = \mathbf{A}\vec{\mathbf{X}}(s) + \mathbf{B}\vec{\mathbf{U}}(s) \tag{5}$$

and

$$\vec{\mathbf{Y}}(s) = \mathbf{C}\vec{\mathbf{X}}(s) + \mathbf{D}\vec{\mathbf{U}}(s) \tag{6}$$

where $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, and $\mathbf{D}$ are matrices describing the open or closed loop systems. For BESSY II, the state, input, and output vectors are

$$\vec{\mathbf{X}}(s) = \begin{bmatrix} V_p(s) & I_1(s) & I_{ps1}(s) & V_a(s) & I_2(s) & I_{ps2}(s) \end{bmatrix}^T, \tag{7}$$

$$\vec{\mathbf{U}}(s) = \begin{bmatrix} X_d(s) & X_1(s) & X_d'(s) & X_1'(s) \end{bmatrix}^T, \tag{8}$$

and

$$\vec{\mathbf{Y}}(s) = \begin{bmatrix} X_e(s) & X_e'(s) \end{bmatrix}^T. \tag{9}$$

The transfer-function matrix, $\vec{\mathbf{H}}(s)$, is

$$\vec{\mathbf{H}}(s) = \left[\vec{\mathbf{C}} \left[s\vec{\mathbf{I}} - \vec{\mathbf{A}} \right]^{-1} \vec{\mathbf{B}} + \vec{\mathbf{D}} \right] \tag{10}$$

where $\vec{\mathbf{H}}(s) = \vec{\mathbf{Y}}(s) / \vec{\mathbf{U}}(s)$. The state variable approach describes the feedback system independent of system order, number of inputs or outputs, or beam transport.

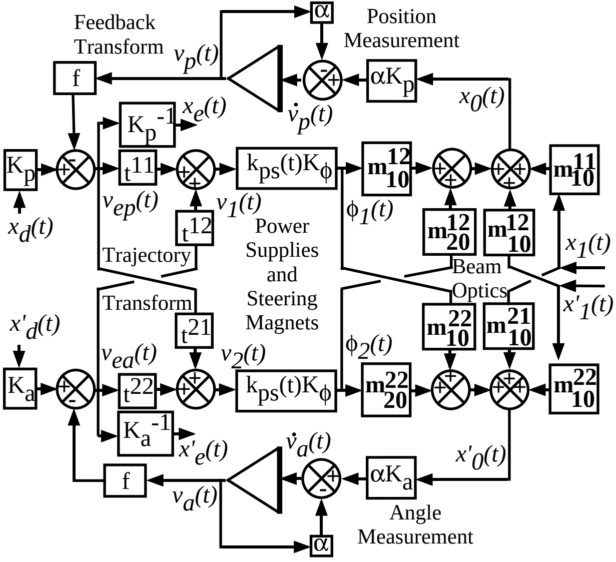

Figure 2: This proportional feedback system has two coupled 3rd order loops.

Substituting BESSY II values into variables of (1) through (4), the transfer function matrix was calculated and simulated with a variety of input signals. $h_{11}(s)$, one of eight transfer-function matrix-elements, is displayed as a Bode plot in Fig. 3. Because the poles, denominator roots of $h_{11}(s)$, are negative (i.e., $s=-7710,-387\pm i3234,-387\pm i3226$), the feedback system is stable.

Beam jitter will be reduced to 21% its original value without feedback and with a bandwidth of 700 Hz. At a particular frequency above 1 kHz, the feedback loop actually amplifies the jitter. However, no higher-frequency beam-jitter sources are likely to exist above a few 100 Hz. This amplification can be completely eliminated at a slight cost to bandwidth by adding another feedback state (e.g., an integral term for a PI type of feedback loop).

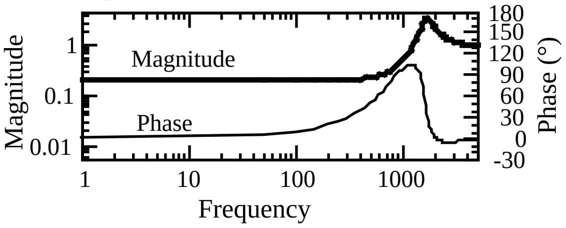

Figure 3: The $h_{11}(s)$ Bode plot shows a 700-Hz bandwidth feedback system reducing the beam jitter to 21% the original value.

Little attempt to optimize the feedback system design was made. However, using state variables to describe the beam measurement and steering dynamics, many optimization design tools are available [3].

4 BEAM FEEDBACK TEST

A simple beam feedback test was performed at BESSY I. Three vertical-steering magnets were used to generate a closed bump. The first magnet was also used with a beam position measurement within the closed bump to implement a feedback system. Since only three bumps were used, t_{12}, t_{21}, and t_{22} were zero. Also, within the three bumps were intervening quadrupole and sextupole magnets, therefore, $\mathbf{M}_{10}$ and $\mathbf{M}_{20}$ were not simple drift matrices. The magnet currents for properly closing the beam bump were determined by two methods. First, by directly calculating the beam transport, and second, by performing fits to the ring beam-position measurements outside the bump.

The steerer magnets inductances, resistances, and K_{ϕ} are 150 mH, 1.4 Ω, and 0.4 milliradians per amp, respectively. Commercially available power supplies with current gains of 2 amps per volt were used. The beam position measurements used processors acquired from LANL and existing BESSY I button electrodes providing a centered-beam position sensitivity of 1 volt per mm [4]. An operational amplifier circuit performed the actual feedback loop closure and provided the closed bump signals for the steerer power supplies.

5 TEST RESULTS

During the feedback tests, a 50-Hz vertical-beam-position variation was discovered at BESSY I. In some ring locations, this variation's maximum peak-to-peak amplitude is 0.03 mm and thought to be a result of a minor failure of a magnet's power supply.

Fig. 4 shows this ripple as measured by beam position measurements inside and outside the closed bump. With feedback applied, the jitter inside the bump was reduced to 39% its original value while a 26% increase to the beam jitter was witnessed outside the bump.

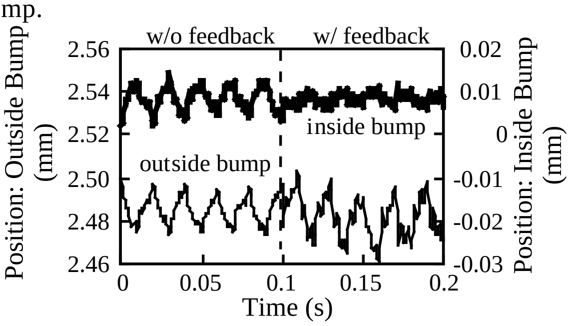

Figure 4: During beam tests at BESSY I, jitter was reduced 61% with beam feedback.

6 CONCLUSIONS

A state variable feedback approach was applied to the beam-position and -angle jitter-reduction problem at BESSY II. Based on the beam transport, a state variable feedback system was designed and simulated. These simulations showed that beam jitter could be reduced to 21% its original value. Also, actual beam feedback experiments were conducted at the BESSY I storage-ring where a 61% reduction of beam jitter was observed.

7 ACKNOWLEDGMENTS

The authors would like to thank Wolfgang Anders, Thomas Westfeld, Winfried Decking, Jens Kuszynski, Peter Kuske, Klaus Ludwig, Detlev Schirmer, and Dietmar Simmering for providing technical support before and during the BESSY I beam tests.

REFERENCES

[1] D. Krämer, "Status of High Brilliance Synchrotron Light Source at BESSY II," published this conference.

[2] S. Khan, et. al., "Layout and Time Domain Simulation of a Local Beam Position Feedback System for BESSY-II," published this conference.

[3] Modern Control Theory, by William L. Brogan, published by Quantum Publishers, Inc., 1974. Digital Control System Analysis and Design, by Phillips and Nagle, published by Prentice-Hall, Inc., 1984.

[4] J. D. Gilpatrick, et.al., "Experience with the Ground Test Accelerator Beam-Measurement Instrumentation," BIW 1993, AIP Conference Proceedings 319, pp. 154-169.