Computer modelling of bunch-by-bunch feedback for the SLAC B-factory design*

D. Briggs, J. D. Fox, W. Hosseini, L. Klaisner,
P. Morton, J.-L. Pellegrin, K. A. Thompson
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309 USA
and
G. Lambertson
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

Abstract

The SLAC B-factory design, with over 1600 high current bunches circulating in each ring, will require a feedback system to avoid coupled-bunch instabilities. A computer model of the storage ring, including the RF system, wake fields, synchrotron radiation loss, and the bunch-by-bunch feedback system is presented. The feedback system model represents the performance of a fast phase detector front end (including system noise and imperfections), a digital filter used to generate a correction voltage, and a power amplifier and beam kicker system.

The combined ring-feedback system model is used to study the feedback system performance required to suppress instabilities and to quantify the dynamics of the system. Results are presented which show the time development of coupled bunch instabilities and the damping action of the feedback system.

I. INTRODUCTION

The large average current in the SLAC B-factory design is distributed into many bunches of sufficiently small charge to minimize the beam-beam interaction and single-bunch instabilities. Although the cavity higher-order-modes (HOMs) will be strongly damped ($Q < 70$), there will still be significant coupling of the longitudinal and transverse motion of adjacent bunches via wakefields. Furthermore, the high-Q accelerating mode can also strongly couple the bunches longitudinally. The resulting instabilities will be controlled via wideband, bunch-by-bunch feedback. Such a feedback system can handle disturbances to the bunch motion arising from any source, including but not limited to wakefields and injection errors.

The feedback systems to control the longitudinal and transverse coupled-bunch instabilities will be similar in architecture. Since the signal detection and kicker requirements are more stringent for the longitudinal system and for the high energy ring (HER), we shall concentrate our discussion on this case. Basic longitudinal-feedback system specifications are shown in Table 1. The proposed system implementation, its block diagram and description, and hardware tests are discussed elsewhere [1].

Table 1: Basic feedback system specifications

RF freq.	476 MHz
Max. mode amplitude	10 ps = 0.03 rad
Injection scheme	1/5 bunch at 60 pps
$\frac{\delta E}{E}$ injection error	0.002
δt injection error	100 ps

* Work supported by Department of Energy contract DE-AC03-76SF00515.

II. SIMULATION MODEL

The simulation model (see Fig. 1) consists of a model of the feedback system electronics, combined with a model of the dynamics of the bunches in the ring.

The feedback system model simulates the transfer function of the feedback system and includes: (1) the electronic properties of the phase detector, mixer, low-pass filter, and A/D converter, (2) input noise, gain and offset errors, bandwidth limitations, and dynamic range of the analog components, and (3) the algorithm running in the set of digital signal processors (DSP farm), that takes as input the digitized bunch phases and calculates the longitudinal kick.

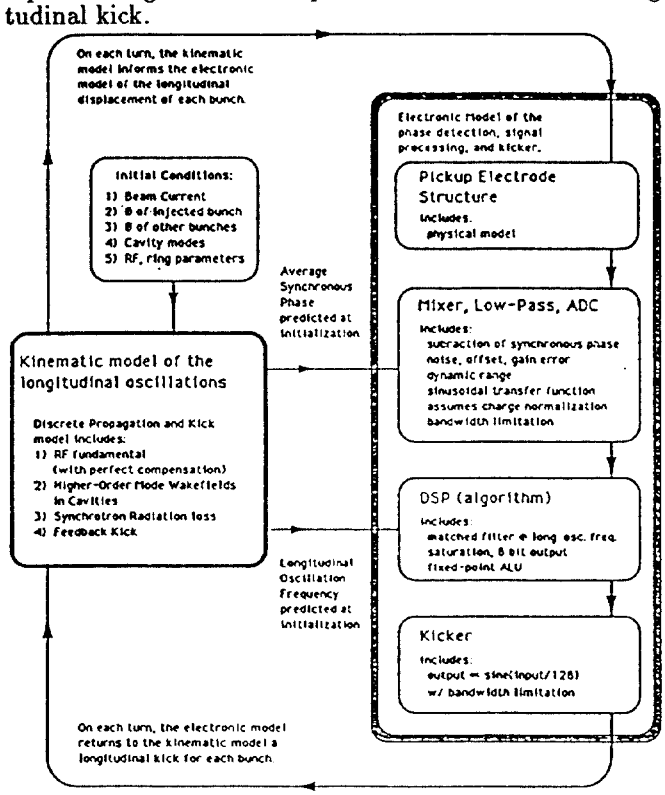

Figure 1. Block diagram of the feedback simulation model.

The model of the DSP farm emulates a 20-tap finite impulse response (FIR) matched filter. The coefficients ξ_j of the taps comprise a sinusoid with the synchrotron period of 19.3 turns, that is,

$$\xi_j = A_{DSP} \sin\left(2\pi \frac{j-1}{19.3}\right) \quad , \tag{1}$$

where $j \in 1, ..., n_{samples}$, and we take $n_{samples} = 20$. Given measures $\tilde{\varphi}_i(k) \equiv \varphi_i(k) - \varphi_s$ (where φ_s is the synchronous phase) of the phase of bunch i on successive turns k as input, the result of the DSP algorithm is the output:

0-7803-0135-8/91$03.00 ©IEEE

$$y_i(k) = \sum_{j=1}^{n_{samples}} \xi_j \tilde{\varphi}_i(k-j) \quad . \qquad (2)$$

This result is clipped to an 8-bit signed integer and used to set the phase of the kicker oscillator for that bunch on that turn. The kicker model is implemented as a phase-modulated RF kicker with a nominal 4 keV maximum output amplitude.

The measurement of the phase of a bunch is assumed independent of its charge, i.e., it is assumed that a separate measurement of bunch charge is available for normalization. A propagation delay of at least one turn (7.33 μs) is enforced in the feedback transfer function.

In the ring simulation model, a discrete kick is given to each bunch at a single point in the ring; that is, the system is modelled as though there were a discrete change in energy at a single point on each turn. This simplification is justified since the synchrotron frequency is small compared to the revolution frequency. The kick given to bunch i is comprised of several components: (1) the RF cavity voltage $\hat{V}_g \sin\varphi_i + V^{cav.fbk.}$, where $\hat{V}_g$ is the peak generator voltage, φ_i is the phase of bunch i with respect to the zero crossing of the RF, and $V^{cav.fbk.}$ is the RF cavity feedback needed to control beam loading in the fundamental mode, (2) the wake field voltage V^{wake} (including both the accelerating mode and the HOM's) accumulated in the cavity up to the present moment, (3) the synchrotron radiation loss per turn, and (4) the voltage V_i^{fdbk} applied to bunch i by the bunch-by-bunch feedback system. Thus, the equation for the total kick is

$$\Delta\dot{\varphi}_i = -\frac{\alpha\omega_{rf}}{E_0/e}\Big[\hat{V}_g \sin\varphi_i + V^{cav.fbk.} - U_0/e + V^{wake} + V_i^{fdbk}\Big] - \frac{2T_0}{\tau_E}\dot{\varphi}_i \quad , \qquad (3)$$

where α is the momentum compaction factor, ω_{rf} is the RF frequency, and τ_E is the longitudinal radiation damping time; E_0 is the ring energy, T_0 the revolution period, and U_0 the synchrotron radiation loss per turn, for a particle on the design orbit. In the present simulations it is assumed that the cavity feedback is perfect, so that the part of V^{wake} due to the fundamental mode is exactly cancelled by $V^{cav.fbk.}$. More realistic models, including the cavity phase, amplitude, and tuning loops, and modification of the impedance at coupled-bunch frequencies that fall within the bandwidth of the fundamental mode [2] are under study [3].

III. SIMULATION RESULTS

Parameters used in the simulations are shown in Table 2. The harmonic number of the HER is 3492, with every other bucket filled except for a 5% gap; the total current is 1.48 A. The initial conditions used were $\varphi_5 = 0.2915$ rad, that is, bunch 5 starts at an 0.1 rad offset from the remaining bunches i, which were started at the synchronous phase $\varphi_i = 0.1915$ rad. The feedback gain in the examples described here was set so that a 5 mrad sinusoid on the input (at the synchrotron oscillation frequency) corresponds to a 4 keV sinusoid on the kicker output.

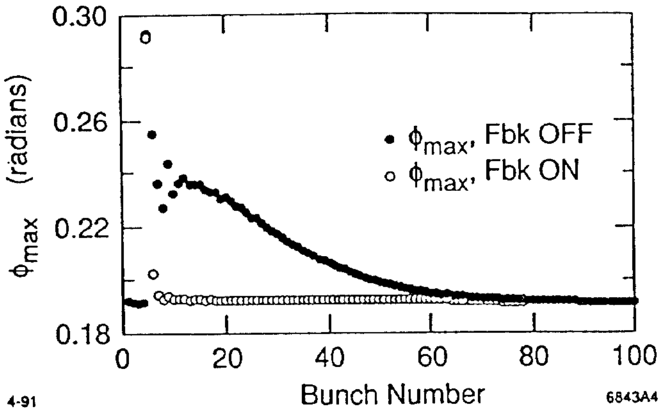

Figure 2. Plot of the maximum bunch offset reached in 3000 turns for the first 100 bunches after the gap, with and without feedback.

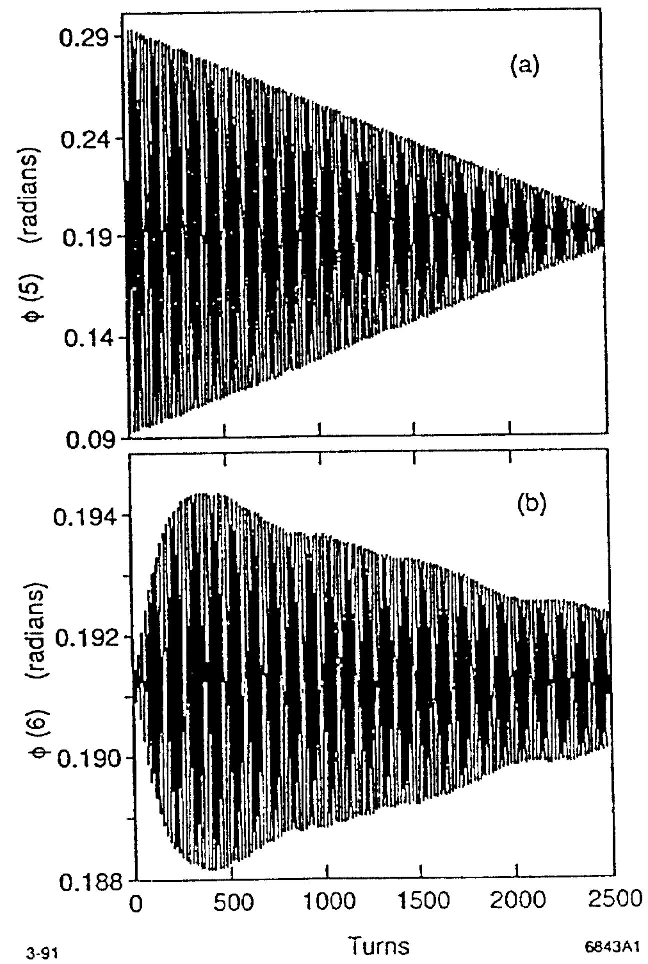

Figure 3. Plots of the longitudinal phases of (a) the injected bunch (#5) and (b) the bunch immediately following (#6), vs turn number, in the presence of feedback. Note the expanded vertical scale in (b).

In Fig. 2, we show a plot of maximum bunch offsets reached after 3000 turns, with and without feedback. Note that the time between injection pulses is 1/60 second, which is about 2300 turns. In the absence of feedback, the disturbance shown would grow even larger and propagate further back in the bunch train. With the feedback system

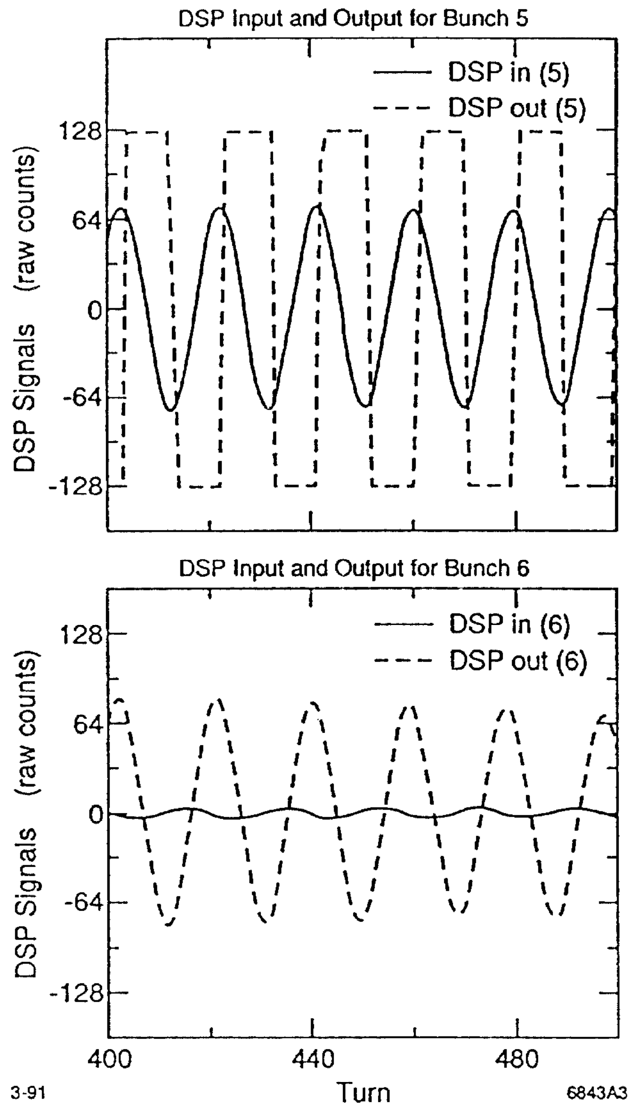

Figure 4. Plots of the input and output of the DSP model for (a) bunch #5, and (b) bunch #6, shortly after the injection of bunch #5.

Table 2: Simulation parameters for HER

Bunch charge	4×10^{10}
Number of bunches	1658
Bunch interval	4.2 ns
Number of cavities	20
Freq. of strongest HOM	750 MHz
Q of HOM	70
R/Q of HOM (per cav.)	33 Ω
$\hat{V}_g$	18.5 MV
α	0.00241
U_0	3.52 MeV/turn

turned on, the coupled bunch excitation does not extend beyond a very few bunches.

Fig. 3 shows the phases of the injected bunch (#5) and the immediately following bunch, vs turn number. The envelope of the phase of the injected bunch damps linearly, reflecting the fact that the kicker saturates, and the phase of the following bunch grows quickly to a maximum and then slowly damps. The excitation of subsequent bunches is strongly suppressed.

Fig. 4 shows the input and output of the DSP model for bunches #5 and #6 shortly after injection. The DSP output saturates for bunch #5, but maintains the proper 90^o phase lag. Such benign saturation behavior is difficult to realize with conventional analog approaches.

Fig. 5 compares the amplitude of the injected bunch #5 and following bunches, first without (Fig. 5a) and then with (Fig. 5b) a 10% bunch-to-bunch coupling in the front-end electronics and a 3% coupling in the kicker. With coupling, bunch #6 suffers a greater disturbance, but still damps, while subsequent bunches suffer only slightly. Thus the system is tolerant of a reasonable amount of bunch to bunch coupling in the analog components.

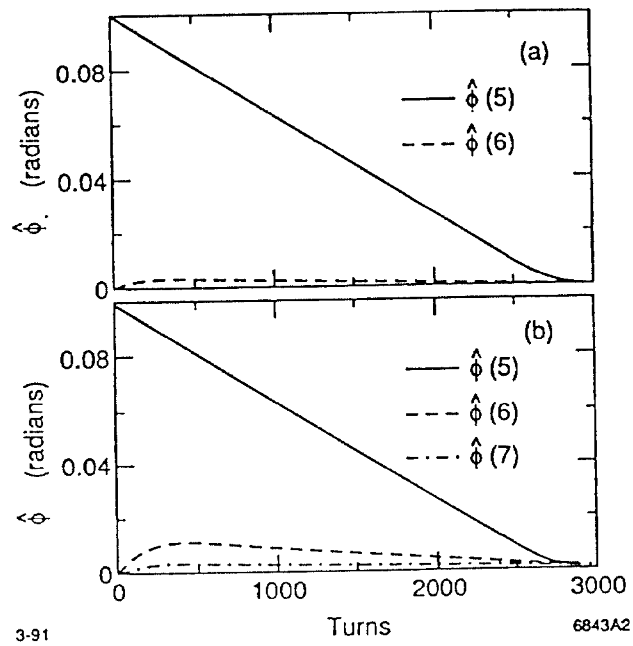

Figure 5. Plots of the phase-space error amplitude for the injected bunch (#5)and following bunch(es), (a) with no coupling, and (b) with 10% bunch-to-bunch coupling in the front-end electronics and 3% coupling in the kicker.

In conclusion, our simulations indicate that the present conceptual approach to bunch-by-bunch feedback is satisfactory. Simulations to support the detailed design effort are in progress.

We thank D. Boussard, J. Galayda, Q. Kerns, F. Pedersen, and P. Wilson for reviewing this work, and J. Dorfan, A. Hutton, and M. Zisman for their interest and encouragement.

REFERENCES

[1] D. Briggs, et.al., "Prompt Bunch-by-Bunch Synchrotron Oscillation Feedback via Fast Phase Measurement", these proceedings.

[2] D. Boussard and G. Lambert, IEEE Trans. Nucl. Sci, NS-30, (1983), p. 2239.

[3] P. Corradoura and F. Volker, private communications.