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Feedback Control of Coupled-Bunch Instabilities*

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Abstract

The next generation of synchrotron light sources and particle accelerators will require active feedback systems to control multi-bunch instabilities [1,2,3]. Stabilizing hundreds or thousands of potentially unstable modes in these accelerator designs presents many technical challenges.

Feedback systems to stabilize coupled-bunch instabilities may be understood in the frequency domain (mode-based feedback) or in the time domain (bunch-by-bunch feedback). In both approaches an external amplifier system is used to create damping fields that prevent coupled-bunch oscillations from growing without bound. The system requirements for transverse (betatron) and longitudinal (synchrotron) feedback are presented, and possible implementation options developed. Feedback system designs based on digital signal-processing techniques are described. Experimental results are shown from a synchrotron oscillation damper in the SSRL/SLAC storage ring SPEAR that uses digital signal-processing techniques.

I. A CLASSICAL ANALOGY

The dynamics of coupled-bunch motion can be illustrated by the mechanical analog of coupled pendulums. In Figure 1 this analogy is applied to the charged particle bunches in a storage ring, with each pendulum representing the oscillatory motion (synchrotron or betatron) of a bunch. The coupling springs represent the impedances of the accelerating cavities and vacuum structures. Bunch_{i+1} and subsequent bunches are driven from the excitations of bunch_i, much as pendulum_i drives pendulums_{i+k} through the coupling springs [4].

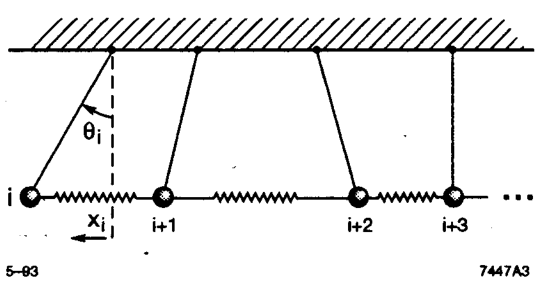

Figure 1. Coupled pendulum analogy.

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In a storage ring with many bunches and many external higher-order mode resonators, the resulting motion can be found by coherently summing the driving terms and considering the periodic excitation due to the orbit of the particles [5,6]. Unstable, growing oscillatory motion can result, in which the motion of a few bunches can excite an unstable normal mode. These instabilities can be controlled by reducing the magnitude and number of external, parasitic higher-order modes, carefully controlling the resonant frequencies of the parasitic resonators to avoid coupling to the beam, and by adding damping to the motion of each bunch.

External beam-feedback systems do the latter. In the analogy of Figure 1, they act to add dashpots to each pendulum. Each bunch can be thought of as a harmonic oscillator obeying the equation of motion

$$\ddot{x} + \gamma\dot{x} + {\omega_0}^2 x = f(t) \ ,$$

where ω_0 is the bunch synchrotron (longitudinal) or betatron (transverse) frequency, $f(t)$ is an external driving term and γ is a damping term. An external feedback system acts on the beam, contributing to this damping term, and allowing control of external disturbances $f(t)$ driving the beam.

II. TIME DOMAIN VS. FREQUENCY DOMAIN PROCESSING

The action of the feedback system can be understood in either the time or frequency domains [7]. If each unstable normal-mode frequency is identified, a single narrowband feedback channel for each mode can be implemented. Such a system consists of a frequency-selective filter (with tailored phase characteristics) and feedback power amplifier for each mode. For a given mode the feedback system acts to generate a driving term which counteracts the excitation from an external resonator. N modes are simply treated as N parallel feedback systems. However, if there are potentially thousands of unstable modes, or the external resonator frequencies or strengths change over time, this narrowband frequency-domain processing is not very attractive or manageable.

The time-domain approach treats each bunch as an independent oscillator coupled to its neighbors through an external driving term. Such a bunch-by-bunch system implements a logically separate feedback system for each bunch in a multibunch accelerator [8,9,10]. In this scheme the coupling to multiple bunches is lumped into a single $f(t)$ driving term in Equation 1.

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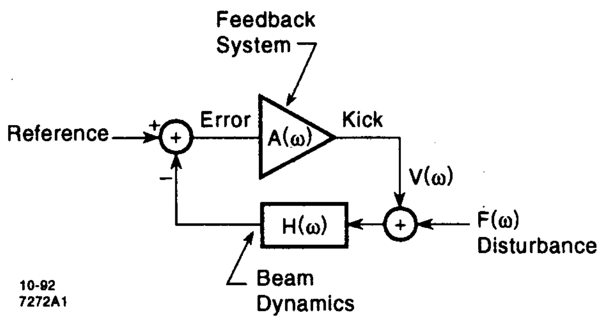

Figure 2. Conceptual diagram of a feedback system $A(\omega)$ acting to stabilize a system $H(\omega)$.

It is important to realize that the input and output signals are identical for both time- and frequency-domain processing. The output signal of a time-domain system contains all the unstable-mode frequency information found at the output of an all-mode frequency-domain system. The approach being implemented cannot be identified if the processing electronics are hidden. The advantage to the time-domain (bunch-by-bunch) approach is the potential to implement a more compact processing block for systems with thousands of bunches and insensitivity to exact knowledge of unstable mode frequencies.

III. FEEDBACK CONTROL

Figure 2 shows a summing node that generates an error signal, a feedback amplifier with complex gain $A(\omega)$, a second summing node that adds an external driving term $F(\omega)$, and a beam-dynamics block with complex transfer function $H(\omega)$.

A disturbance $F(\omega)$ applied to the system is reduced by the feedback amplifier by the amount

$$\frac{H(\omega)}{1 + A(\omega)H(\omega)}.$$

As the dynamics of the beam $H(\omega)$ are determined by accelerator design, the challenge to the feedback designer is to specify $A(\omega)$ so that the loop is stable, the response to disturbances $V(\omega)$ is bounded, and the transients are well damped.

Both longitudinal and transverse feedback systems can be described by Figure 2. For the transverse case, the input set point is the desired orbit mean coordinate, and the output signal is applied via a transverse electrode assembly which acts with a transverse kick on the beam. For the longitudinal case, the set point refers to the desired stable bunch phase or energy, and the correction signal is applied to the beam to change the bunch energy [19].

One fundamental difference between longitudinal and transverse accelerator feedback systems is the ratio of the oscillation frequency ω_0 to the revolution (sampling) frequency ω_{rev}. If $\omega_{rev} \geq 2\omega_0$, the Nyquist sampling limit is not exceeded and spectral information is not lost. As synchrotron frequencies are typically lower than revolution frequencies, the sampling process does not alias the longitudinal oscillation frequency. However, in the transverse case, betatron frequencies are greater than revolution frequencies, and the sampling process aliases the oscillation to a different (aliased) frequency. Thus, the transverse signal processing must operate at an aliased frequency, and be capable of operating over a range of aliased frequencies representing the machine betatron-tune operating range. A general-purpose processing block for transverse feedback may be implemented using two beam pickups $\pi/2$ apart in betatron phase, and combining these signals in a quadrature phase shifter. This approach allows flexibility in the location of the kicker with respect to the pickups, and allows adjustment for machine tune via scaling of the quadrature coefficients [11].

IV. SIGNAL PROCESSING OPTIONS

The feedback path $A(\omega)$ in Figure 2 has several functions:

Detect the bunch oscillation.
Provide a $\pi/2$ phase shift at the oscillation frequency.
Suppress DC components in the error signal.
Provide feedback loop gain at ω_0.
Implement saturated limiting on large oscillations.

These requirements are met by a differentiator, or a bandpass filter centered at the oscillation frequency ω_0, with some specified gain and a $\pi/2$ phase shift at ω_0. DC rejection of the filter is necessary to keep the feedback system from attempting to restore a static equilibrium position to an artificial set point. The filter should also reject signals above the oscillation frequency to prevent noise or other high-frequency signals from being mixed down into the filter passband and impressed onto the beam. The limiting function allows injection (and large-amplitude excitation of the injected bunch) while still damping neighboring bunches in a linear regime. The saturated processing has been shown to suppress the growth of coherent instabilities from injection-like initial conditions [12].

For systems with thousands of bunches, an efficient processing approach is to take advantage of the inherent sampling at ω_{rev}, and implement the filter as a discrete time filter of either finite impulse response (FIR) or infinite impulse response (IIR) forms. A FIR filter is a convolution in the time domain

$$Y_k = \sum_{n=0}^{m-1} C_n X_{k-n}$$

where Y_k is the filter output on sample k, X_k is the filter input on sample k, and m is the length of the filter (or number of past input samples used to generate an output).

There are many possible forms of filter that are adequate for the beam feedback task [19]. Pure delays and differentiator or bandpass functions can be specified to implement the required $\pi/2$ phase shift. One possible filter is a differentiator using two taps spaced roughly $\pi/6$ of an oscillation cycle apart. If the tap spacing is $\pi/2$ of the synchrotron period, a two-tap bandpass filter can be created.

Choosing among the many possible filters requires tradeoffs in signal-to-noise (the differentiators emphasize high frequencies) and in the complexity of the filter.

These filters can be realized by several approaches. All-analog approaches are possible, in which the required feedback filter is implemented as a transversal filter comprised of several stages of tapped delay lines. Dispersion and losses in the delay line must be matched to the filter properties. For example, a full oscillation-period longitudinal filter for a PEP-II-like facility (136 kHz ω_{rev}, 7 kHz ω_s) with 4 ns spacing between the bunches would require a total delay time of roughly 140 μs with a signal bandwidth of greater than 125 MHz, or a τ B product of 2×10^4. Only optical delay $\tau B_{max} = 10^6$ lines allow adequate bandwidth-delay product to implement the PEP-II filter. Longitudinal filters for the SSC or LHC machines, with their several Hz synchrotron frequencies and 60 MHz bunch-crossing frequencies look even more challenging, requiring τB products of greater than 10^6 for a full-period filter.

In contrast, digital signal-processing techniques look very attractive as the means to implement these feedback filters. One interesting feature of the time-domain processing scheme is that the feedback process uses only information from a particular bunch to compute the feedback signal for that bunch. It is therefore possible to implement a parallel processing strategy and spread the high sampling-rate bunch information among several slower computing blocks.

For longitudinal feedback ω_{rev} is typically much higher than the oscillation frequency ω_s, and it is possible to implement a downsampled processing channel. In a downsampled scheme the information about a bunch's oscillation coordinate is only sampled once every n revolutions, and a new correction signal only updated once every n crossings [13]. This approach reduces the number of multiply-accumulate operations in the filter by a factor of $1/n^2$. Table 1 shows the aggregate filter complexity (in MACS/sec) for downsampled five-tap filters and non-downsampled two-tap filters for five accelerator facilities. The advantage of downsampling in reducing the aggregate MAC rate is clearly seen. The filter complexity linearly scales with the MAC rate in terms of storage required and speed of the operations. Large facilities with low synchrotron frequencies are especially good candidates for downsampled processing. For example, the SSC design, with a 3.4 kHz revolution frequency and a 4–7 Hz synchrotron frequency, samples the bunch information 500 to 850 samples per cycle, or 250–400 times the Nyquist limited rate. The downsampled processing technique allows the use of arrays, or "farms," of commercial single-chip DSP microprocessors to compactly implement feedback systems for thousands of bunches. This approach is particularly well-matched to the commercial activity in digital signal-processing microprocessors.

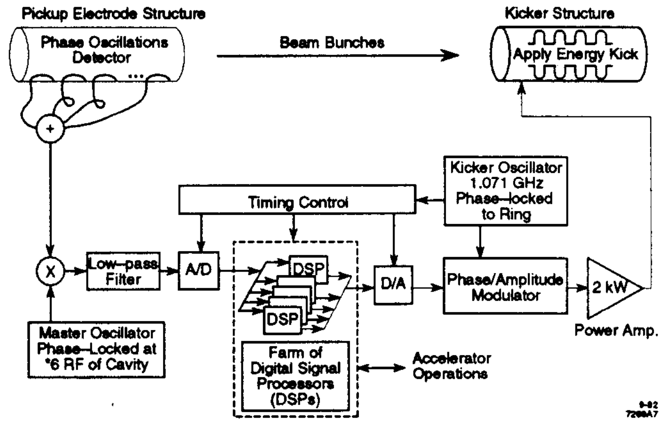

Figure 3. Block diagram of the PEP-II longitudinal feedback system.

Table 1.
Filter Complexity for Five Accelerators.

Parameter	PEP-II	ALS	DAϕNE	SSC	LHC
Number of bunches	1746	328	120	17424	5940
τ revolution (sec)	7.3 E-6	6.6 E-7	3.2 E-7	3 E-4	9 E-5
τ synchrotron (sec)	1.4 E-4	7.9 E-5	2.6 E-5	.24	1.3 E-2 (min) 4.8 E-2 (max)
τ_s/τ_r	19.2	121	79.8	814	150 (min) 540 (max)
Filter MACS/sec 2 TAP non-downsampled	5E8	1E9	7.4 E8	1.2 E8	1.3 E8
Downsampling Factor	4	24	16	161	30 (min) 108 (max)
Filter MACS/sec Downsampled 5 TAP	3E8	1E8	1.2 E8	2 E6	1 E7 (min) 3 E6 (max)

V. OPERATION OF A DSP FEEDBACK SYSTEM AT SPEAR AND ALS

Figure 3 shows the essential components of the PEP-II longitudinal-feedback system in development at SLAC [14,15]. This design was selected for use by the PEP-II B factory, the LBL Advanced Light Source (ALS), and the Frascati ϕ factory DAϕNE [16]. A prototype system was constructed incorporating an eight-tap stripline comb generator, a master-phase reference oscillator, a phase detector, 250 MHz A/D and D/A stages, and an AT&T 1610 DSP microprocessor.

The prototype feedback system was tested in September 1992 using the SPEAR storage ring at SLAC, and in April 1993 on the ALS at LBL [17]. For this experiment the beam was sensed via a button-type BPM electrode and processed by the prototype B factory front end. The DSP feedback signal was used to control a phase shifter acting on the rf cavity phase, which closed the loop around

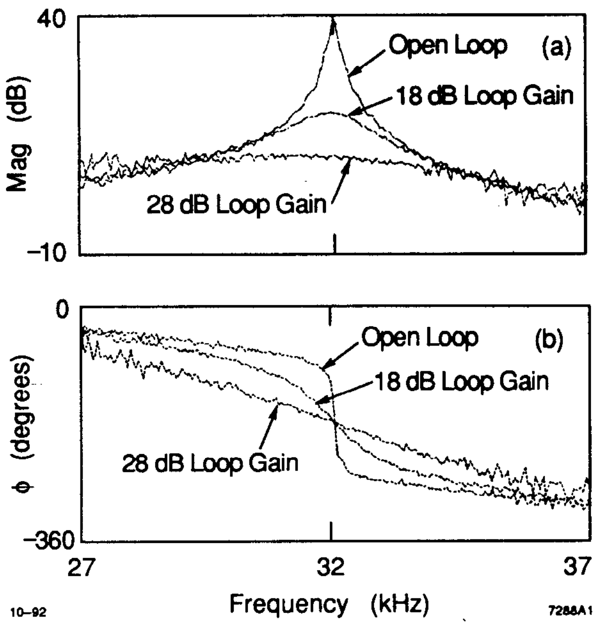

Figure 4. Magnitude(a) and phase(b) response for a single bunch for open-loop and closed-loop gains of 18 and 28 dB. The associated Q factors are 200 (open loop), 20 (18 dB) and 5 (28 dB).

the stored beam. The feedback filters used in these experiments are the same type proposed for PEP-II (five-tap FIR bandpass filter), with a downsampling factor of eight (SPEAR) or twenty-five (ALS).

The SPEAR and ALS storage rings do not have a wideband kicker of the type proposed for PEP-II [18]. The systems implemented used one of the two main rf accelerating cavities to apply corrections to the beam. As the bandwidths of the rf systems are limited to 40 kHz and 20 kHz, it is not possible to implement true multibunch feedback systems. Therefore, all of the closed-loop measurements were performed using a single stored bunch demonstrating the behavior of a single bunch acted upon by a digital feedback system. An additional series of open-loop measurements were made with the rings filled with multiple bunches, which allows multi-bunch coupling to be observed but not controlled.

Figures 4a and 4b show the magnitude and phase responses of the SPEAR beam-transfer function for an open-loop configuration, and for closed-loop gains of 18 and 28 dB. In this figure the open-loop response shows a weakly damped harmonic oscillator as described by Equation 1, with a Q of 200. The natural damping present in this case is due to Robinson damping as well as radiation damping. We see in the figure the action of the feedback system to increase the damping term in Equation 1, and lower the Q of the harmonic oscillator. The configuration with 28 dB of loop gain barely displays any resonant behavior (Q = 5), and suggests that the transient response of the combined system will damp in a few cycles.

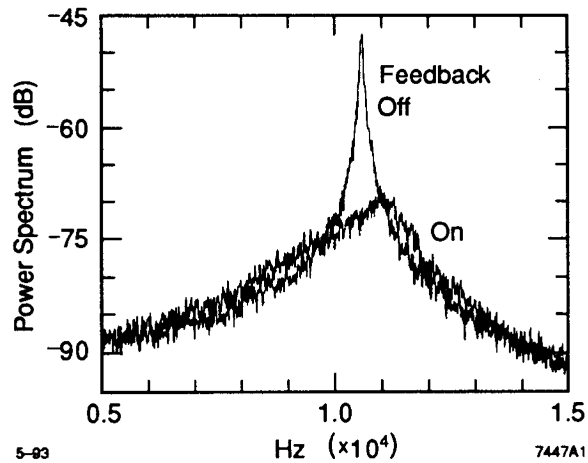

Figure 5. ALS power spectra for open loop and 31 dB loop gain.

Figure 5 presents power spectra of the ALS bunch motion for single-bunch operation with the feedback system operated open loop and with 31 dB loop gain. In this measurement a broadband noise source is used to excite the beam through the rf cavity. The figure shows a 28 dB reduction in the magnitude of the synchrotron oscillation due to the external damping provided by the feedback system.

The time response of the system can be observed in Figure 6. In this experiment the feedback loop is opened, and a gated burst at the synchrotron frequency is applied via the rf cavity. This excitation burst drives a growing synchrotron oscillation of the beam. The excitation is then turned off and the feedback system loop closed. Figure 6a shows the free decay of the SPEAR beam in which the damping-time constant (e folding time) in the absence of feedback is 2 ms. Figure 6b shows the damping transient of such a gated burst for a 33 dB loop-gain configuration which reduces the damping time constant to 40 μs.

To quantify the equilibrium noise performance of the damping system the rms bunch phase was measured at the completion of the damping transient. These measurements reveal that the residual beam motion is roughly 2.5 mR at 358 MHz (3% of the 1.4 cm bunch length), corresponding to a time jitter of 1 ps. The quantizing interval for the system as configured at SPEAR was 2.7 mR, indicating that the feedback system acted to damp excitations and noise to within the front-end quantization interval.

VI. SUMMARY

Multibunch feedback systems may be understood as electronic systems which add damping to the motion of particles in an accelerator. The systems may be designed using frequency- or time-domain formalisms. An example system which uses digital signal processing has been tested at SPEAR and the ALS. These system measurements have shown the operation of all the essential detection and processing components required for the PEP-II longitudinal-feedback system. The fast front-end circuits were demon-

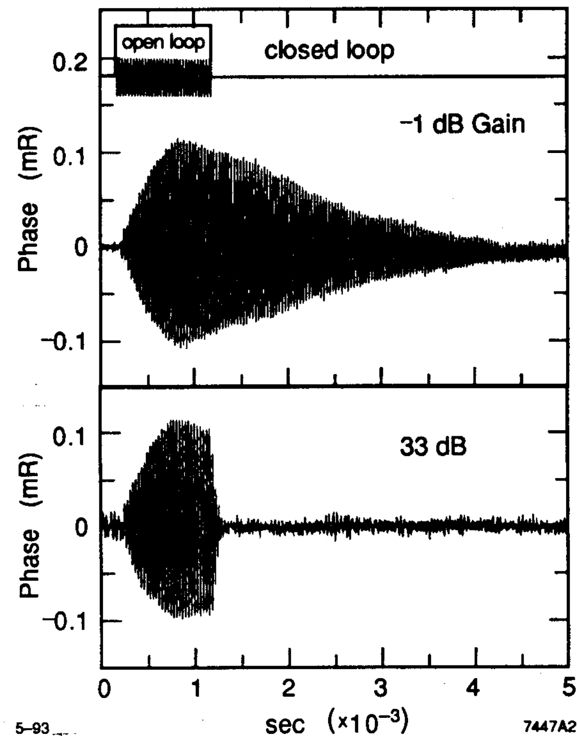

Figure 6. Time response of a SPEAR excited bunch—open-loop response in 8a, 33 dB loop gain in 8b.

strated with the required 4 ns bunch spacing, and the digital signal-processing filter proved for linear and saturated modes. The digital filter-signal processing provides a very flexible and general-purpose feedback system which is easily configured to operate for varied operating facilities.

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