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Control of Multibunch Longitudinal Instabilities and Beam Diagnostics Using a DSP-based Feedback System

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Abstract

A bunch-by-bunch longitudinal feedback system has been designed and built to control coupled-bunch instabilities in the PEP-II machine. A prototype system has been installed at the Advanced Light Source at LBNL. Programmable DSPs allow longitudinal feedback processing in conjunction with data acquisition or instrumentation algorithms. Here we describe techniques developed for different beam and system diagnostics, such as measurements of the modal growth and damping rates and measurements of the bunch-by-bunch currents. Results from the Advanced Light Source are presented to illustrate these techniques.

1 SYSTEM OVERVIEW

The multibunch longitudinal feedback system for use by PEP-II, ALS, and DAΦNE is designed using a modular family of analog and digital VME and VXI modules. The principles of operation and detailed description of the system design are given in earlier publications [1], [2], [3].

2 TRANSIENT RECORDING TECHNIQUES

One interesting feature of the programmable system is the capability to use the memory and features of the digital signal processors for machine and system measurements. The programmable algorithms in the DSP can be completely user specified, so that a program can excite the beam for a short interval, run different control algorithms at various times (such as injection) or simply record the bunch motion as the feedback system operates. Such digital data records provide a very powerful diagnostic capability to observe and quantify the motion of the particles in the storage ring. The record functions allow a snapshot of the controlled beam motion, from which the system noise floor and the power spectrum of external disturbances driving the beam can be obtained. Observing the motion as the feedback system is turned off displays the growth rates of the unstable modes, while recording the motion when the feedback signals are turned back on reveals the net damping in the system. Frequency domain information can be computed from these time-domain data sets via use of Fourier transform techniques.

An example measurement using this grow-damp technique is illustrated in Figure 1. In this experiment at the LBL Advanced Light Source the beam is initially stable under the action of the feedback system. Under software control the feedback gain is set to zero, and after a holdoff interval the DSP processors start recording the bunch motion. For $t_{holdoff} < t < t_{on}$ the growing bunch oscillations are recorded, and at t_{on} the feedback gain is restored to the operating value. The motion (now a damping transient) continues to be recorded until t_{max}, at which time the DSP's stop recording, but continue computing the feedback signal (controlling the beam). The data records are stored in a dual-port memory which is accessible to an external processor (the total record length is 960 samples of each of 324 bunches).

If the data is arranged in a 2 dimensional array of bunch vs. sample number, each row (containing the oscillation coordinate of each of 328 bunches sampled on a single turn) can be Fourier analyzed to express the bunch coordinates in a modal representation. This Fourier transform is computed for each sampling time (turn number) in the array. Figure 1 presents such a growth-damp modal plot (taken at the LBL Advanced Light Source) which shows the presence of two modes of oscillation in the transient. The growth rates and damping rates for each mode can be found from this data set via the numeric fitting of exponential curves to the data. The modal plot directly shows the action of the feedback system in turning the net growth rate from positive to negative at the time the feedback system is switched back on [4].

Another method of analyzing the transient time-domain data is to concatenate the sampled bunch phases over a

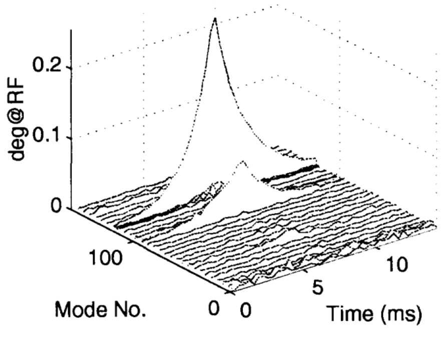

Figure 1: Plot of a turn by turn FFT of the bunch data, revealing two unstable modes (mode 95 and 124) of 328 bunches in the ALS over a 12 ms time interval. The feedback system is on for t<0 and t>6 ms, and off for 0<t<6 ms. Unstable bunch motion grows during the feedback off interval. The total machine current was 120 mA.

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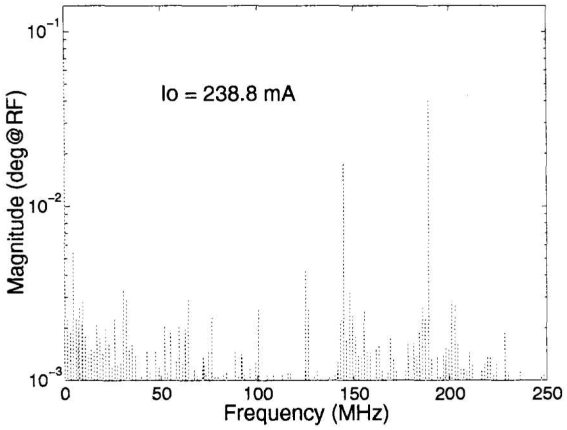

Figure 2: Magnitude of high-resolution FFT of growing transient in Fig. 1, showing all the spectral components over a 250-MHz bandwidth.

few milliseconds and take the FFT of the resulting vector. The beam pseudospectrum resulting from a single 4-8 ms transient covers the entire 250 MHz range of the modes with a resolution of 250-125 Hz. The distance of the sidebands from the revolution harmonics gives us the frequency shifts of the modes, and the width of the sidebands gives us an equivalent way of calculating their growth rates. Figure 2 shows the magnitude of the FFT of the bunch-phase signal over the last 4 ms of mode growth from a transient measurement at the ALS. The beam pseudospectrum spans 250 MHz with a frequency resolution of 250 Hz - the figure shows several large spectral components due to the unstable coupled-bunch motion [5]. The pseudospectrum contains information around every revolution harmonic in the 250 MHz span, though the revolution harmonics themselves are suppressed due to the sampling of the bunch motion in the feedback system.

Fig. 3 zooms in on a 70 kHz section of the 250 MHz spectrum in Fig. 2. It shows that the most unstable mode is an upper sideband at $204f_{rev}$ (and therefore a lower sideband at $328-204 = 124f_{rev}$), with a linewidth corresponding to the previously measured growth rate. The lower sideband is damped to the noise floor by the TM-011 cavity mode. The next most unstable mode in figure 2 is an upper sideband at $233f_{rev}$ (and therefore a lower sideband at $95f_{rev}$). In contrast to these transient techniques, a measurement using a heterodyned spectrum analyzer would take at least a few minutes to perform the 328 narrowband sweeps required to produce an equivalent spectrum, by which time the oscillations would have reached a damped or saturated steady state. For the PEP-II machine, with a harmonic number of 3592, the advantage of the transient - base technique over several thousand narrowband heterodyned measurements is even greater.

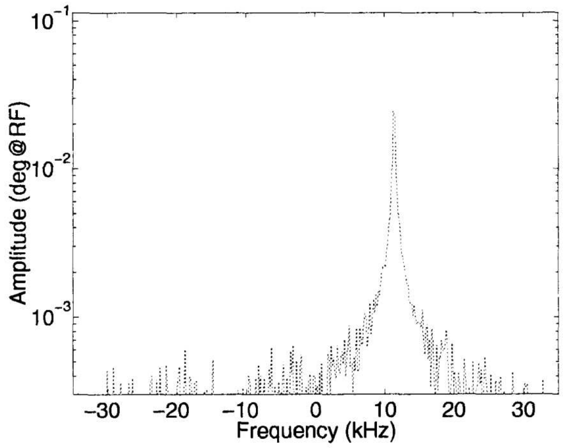

Figure 3: 70 kHz section of the high resolution spectrum in Fig. 2, showing an unstable upper sideband and a damped lower sideband at $204f_{rev}$.

3 BUNCH-BY-BUNCH CURRENT MEASUREMENT TECHNIQUES

Analysis of the modal patterns is complicated by any non-uniformity of the fill pattern. An important piece of data for such analysis is the bunch current distribution. Two different techniques have been developed that allow the longitudinal feedback system to measure the bunch-by-bunch current distribution. The first method requires a system dedicated to the current measurement (the system is reprogrammed to act as a current monitor). A second approach has been developed which allows measurement of the per bunch current without affecting the longitudinal feedback processing.

3.1 Dedicated current measurement technique

In the feedback mode of operation the system is set up to detect the phase of the bunches with respect to a reference oscillator using a double balanced mixer. If the reference oscillator phase is set to a nominal bunch synchronous phase the digitized signal corresponding to bunch *k* is

$$s_k = Gq_k \sin\phi_k$$

In the above equation q_k is the charge, ϕ_k is the phase of bunch *k*, and *G* represents the front-end gain. To measure beam currents the phase of the reference oscillator is shifted by 90°. Then at the A/D converter we get

$$s_k = Gq_k \cos\phi_k$$

If every bunch is riding on an identical synchronous phase this method directly measures the charge per bunch, however if there is a beam loading transient each bunch has a unique synchronous phase and the s_k does not simply measure the per bunch charge. In order to extract the bunch current from this measurement each bunch signal is sampled at 70 kHz in the DSP farm. These signals exhibit significant variations due to synchrotron oscillations as well as low frequency synchronous phase motion. The DSP array is programmed to downsample the data using windowed peak detection with a 256 sample window. As a result we obtain a 3.6 second long record at a 270 Hz sampling rate. A windowed peak detection algorithm eliminates noise due to the synchrotron motion, but

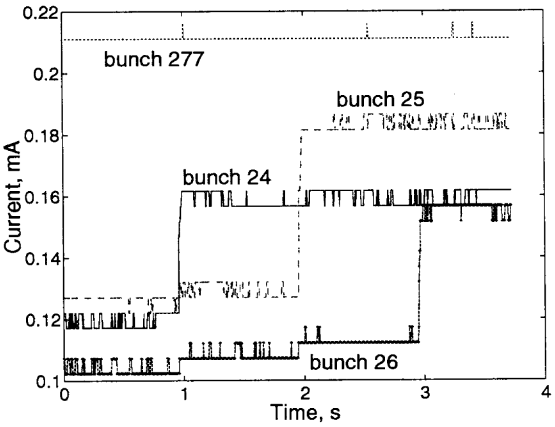

Figure 4: The bottom traces show injection into 3 consecutive buckets 2 ns apart, while at the top previously injected bunch is shown.

synchronous phase motion at the line frequency is still present. The output of the peak detector is post-processed off-line using a 5-sample median filter. The sensitivity of this approach is 5 μA with 2.5 μA RMS noise. Full-scale range is 1.2 mA/bunch. Figure 4 shows current monitor data taken during injection at the ALS. The consecutive bunches are being injected at 1 Hz rate.

3.2 Frequency-division current measurement method

A technique has been developed that allows current measurement in conjunction with feedback processing. In the frequency-division method the front-end reference oscillator is operated at a nominal synchronous phase, which maximizes the phase detector sensitivity to synchrotron motion. A sinusoidal phase modulation ($f_{cm} = 2kHz$) is applied to the local oscillator at a frequency significantly below the synchrotron resonance and a second modulation frequency ($f_{sweep} = 70Hz$)is used to sweep the operating point of the phase detector. The input signal at the A/D for small motion ($\sin x \approx x$) is given by

$$s_k = Gq_k(\phi_k + \sin\omega_{cm}t + \sin\omega_{sweep}t)$$

A time record of all bunches is taken by the DSPs and processed off-line using envelope detection. The signal envelope of each bunch is bandpass filtered around the fast modulation frequency, and the magnitude of the peaks in the envelope waveform represents the current of that bunch. Figure 5 shows the current versus bunch number for the square wave fill that is used to study mode coupling. During this current measurement the feedback system continues to control the beam instabilities. The resolution of this technique is found to be 7 μA with a 1 mA/bunch full-scale.

5 SUMMARY

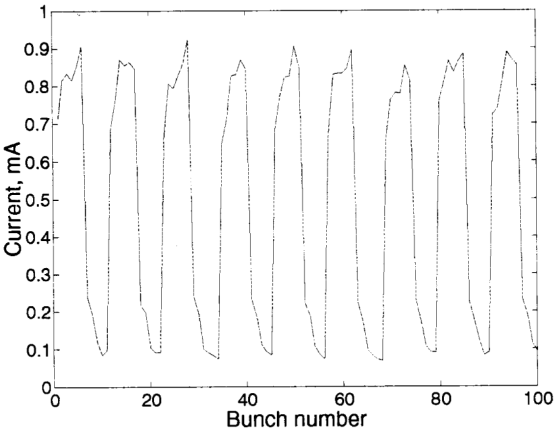

Figure 5: Current measurement for a square wave fill

The time domain transient techniques illustrated require only a few milliseconds of beam motion and are essentially invisible to users of the storage ring. The information obtained from the analysis of the time domain data reveals growth rates and damping rates of beam modes, bunch current distributions and is very useful in adjusting the feedback system or as a quick check on its operation. The general-purpose signal processing capabilities of the DSP farm allow new instrument modes and new measurements to be rapidly developed and integrated into the system software.

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