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Down Sampled Signal Processing for a B Factory Bunch-by-Bunch Feedback System*

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Abstract

A bunch-by-bunch feedback scheme is studied for damping coupled bunch synchrotron oscillations in the proposed PEP II B Factory. The quasi-linear feedback system design incorporates a phase detector to provide a quantized measure of bunch phase, digital signal processing to compute an error correction signal and a kicker system to correct the energy of the bunches. A farm of digital processors, operating in parallel, is proposed to compute correction signals for the 1658 bunches of the B Factory.

This paper studies the use of down sampled processing to reduce the computational complexity of the feedback system. We present simulation results showing the effect of down sampling on beam dynamics. Results show that down sampled processing can reduce the scale of the processing task by a factor of 10.

INTRODUCTION

In [1] a design for a digital bunch-by-bunch feedback system was introduced for damping the coupled bunch synchrotron oscillations in the proposed PEP II B Factory. The basic idea behind this approach was to treat each bunch in the time domain as an individual oscillator. The phase oscillations of each bunch relative to the RF are detected and a feedback signal is applied to each bunch which is proportional to the detected bunch phase but phase shifted by 90° (and therefore 180° out of phase with its energy). As stated in [1], this approach has the added advantage that it damps out any disturbance, not just coupled bunch oscillations.

The computation of the feedback signals is performed by a 'farm' of commercially available Digital Signal Processors (DSPs). These DSPs would all execute the same program, and each DSP would be responsible for computing the feedback correction signals for some group of bunches. The number of bunches that a DSP can process depends on the speed of the processor, the complexity of the algorithm for computing the feedback signal (the digital filtering) and the overhead costs in data transfer and distribution. It was estimated that approximately 480 such processors would be required to implement the system proposed in [1] for the PEP II B Factory. However, recent studies [2,4] have shown that by making use of a technique called *down sampling* it is possible to reduce the number of processors to approximately 50.

IMPLEMENTATION OF DOWN SAMPLING

The technique of down sampling exploits the redundancy in the data to reduce the computational burden on the feedback system. Since the phase oscillations are roughly sinusiodal, according to the Nyquist theorem it is possible to detect the amplitude and phase of these oscillations using as little as two samples per period. The original system used 19, which is clearly redundant.

Since the feedback system is a bunch-by-bunch feedback system, it is sufficient for our purposes to think of the problem as that of damping a single bunch, while bearing in mind that the same operations are being carried out on all the other bunches. This is shown in Figure 1 which corresponds exactly to the original system in [1], except for the two new outlined components.

By introducing the down sampler into the loop in Figure 1, only one out of every n samples is allowed to get to the digital filter and the remaining n-1 samples are simply rejected. The hold buffer placed at the output of the DSP simply *repeats* the most recent kick value for the remaining n-1 turns. This is called down sampling by a factor of n. In this way, the wideband kicker is used efficiently to change the energy of the bunch on

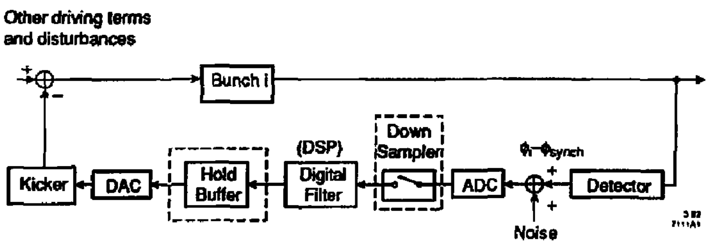

Figure 1. Conceptual design of bunch-by-bunch feedback system. The phase of each bunch is detected and a feedback kick particular to that bunch is computed and applied by the kicker. The down sampler allows the DSP filter to run at a slower rate, while the hold buffer repeats the most recent kick until the new kick is computed.

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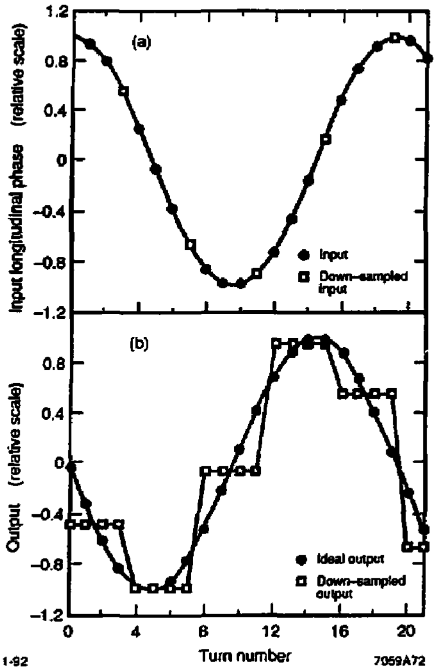

Figure 2. Response of the down sampled filter with hold buffer: (a) shows the input samples, the squares are sampled values of longitudinal oscillation, taken once every fourth turn; (b) shows ideal non-down sampled output and the down sampled and held outputs.

every turn. The kicker signal that is applied to the bunch is now a coarser approximation to the ideal feedback kick (Figure 2).

The DSP must now operate on only $1/n$ of the original amount of data to compute the correction signal. In addition, it now has n times longer to perform this task. Thus the number of computations per unit time that the DSP must perform on each bunch is reduced by a factor of $1/n^2$. This reduction in the processing load per bunch per unit time means that a given DSP can now process more bunches. This process reduces the complexity of the system as a whole and leads to a greatly simplified processing system.

Our results will show that the optimum down sampling factor for our system was $n = 4$, beyond which the quality of the beam dynamics began to suffer.

THE DIGITAL FILTERS

The DSPs compute the correction signal for each bunch using an FIR (finite impulse response) digital filter algorithm. The output of an FIR filter is the convolution of the input with the impulse response of the filter:

$$y(i) = \sum_{m=0}^{N-1} c(m)\phi(i-m) \qquad (1)$$

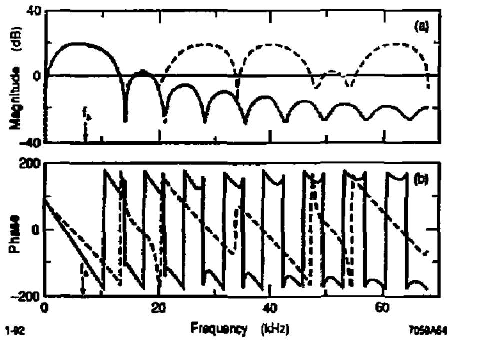

Figure 3. Frequency responses in (a) magnitude and (b) phase. Solid lines show the $n=1$ case and dashed lines the $n=4$ case, as determined by the Fourier transform of the coefficients. In the simulation, the phase response is 90° at the synchrotron frequency for both cases, due to the delays in the hold buffer.

where the coefficients $\{c(m)\}$ are the impulse response of the digital filter, and the $\{\phi(n)\}$ are past N values of the input, in our case, the phase error measurements of a bunch.

The coefficients of the FIR filter implement a correlation to detect the oscillation phase. The filter in the original design had $N = 20$ coefficients, whereas the down sampled filter has only $N = 5$ coefficients (for down sampling by $n = 4$) because only five samples per period are taken.

The frequency responses of the 20-tap and 5-tap filters are shown in Figure 3 . We note that the gain of the filters is equal at the synchrotron frequency f_s, and that the phase of the down sampled filter has been deliberately advanced so that the sum of the delays due to the filter and the hold buffer is -90°. Another important characteristic of these filters is that they are designed to have essentially zero dc response. This means that the feedback correction signal will drive each bunch to its own equilibrium phase wherever that may be.

RESULTS

In this section, the performance of a non-down sampled feedback system is compared to $n=2$ and $n=4$ down sampled systems.

Computer simulations were performed on an accelerator model with ten bunches in which all bunches but the fifth start at equilibrium [3]. The fifth bunch is perturbed by 100 mrad to simulate injection. The whole system is then observed until all bunches are damped to steady state. The simulations included 5% of full scale white noise in the phase measurements and a single higher order mode in the cavity. Table 1 shows the feedback system parameters which were kept constant for all three cases.

The effects of down sampling on the beam dynamics were compared quantitatively using figures of merit.

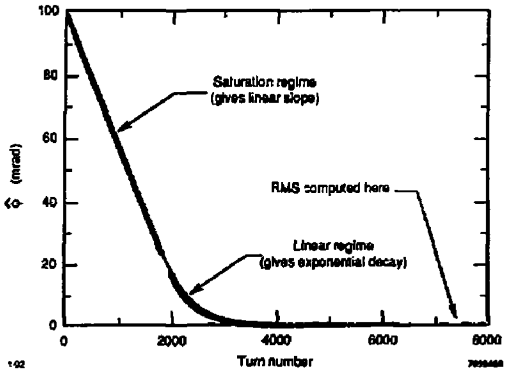

Figure 4. Plot of the phase-space error amplitude for an injected bunch, indicating the operating regimes used to compare filters.

Table 1: Simulation system parameters

Linear midband filter gain	100 V/mrad
Input quantization size	1.3 mrad
Output quantization size	50 V
Input noise amplitude (rms)	8.3 mrad
Kicker saturation voltage	4 kV

These are shown in Figure 4.. The slope in the saturated feedback region is a measure of the the efficiency of the feedback during the period when the phase deviation is so large as to saturate the feedback system. The slope upper bound is determined by the kicker power while an incorrect phase shift in the filters can reduce it. An exponential fit to the region where the feedback system is operating linearly gives an exponential damping time constant. This is determined by the overall gain of the system at the synchrotron frequency. The steady state behavior is quantified by the rms of the phase deviations from the equilibrium phase.

Table 2 shows the figures of merit for the transient behavior. These figures remain essentially constant as the down sampling factor is increased. We conclude that $n=2$ and $n=4$ down sampling has no significant effect on the transient damping dynamics of the beam.

Figure 5 shows the rms phase error in steady state versus down sampling factor for four bunches roughly equally spaced through the bunch train of the ten bunches. The rise in rms phase error with down sampling factor is mainly the result of the down sampled filters being more broad band than the non-down sampled one (see Figure 3). An equivalent time domain argument is that for higher n, we have fewer coefficients, and are therefore sampling fewer data points and thus less able to average out the uncorrelated noise (see Equation 1). However, although the rms phase error for each bunch rises with down sampling, they are all kept to within 0.65 mrad, one-half of the quantizing resolution of the input. Thus we conclude that for $n=2$ and $n=4$ the down sampling has no significant effect on the steady state characteristics of the beam.

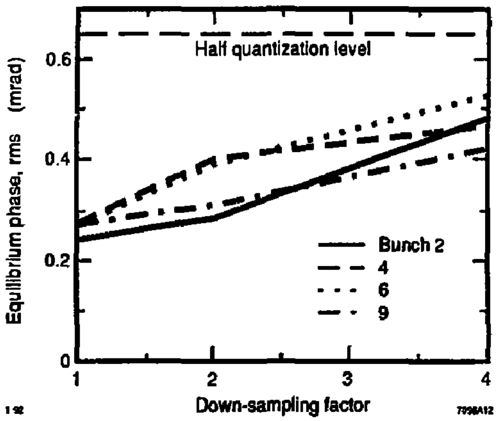

Figure 5. Performance comparison, for several bunches, of the three filters ($n=1,2,4$) in terms of equilibrium rms phase noise.

Table 2: Simulation saturation slopes and exponential decay time-constants

	20-tap (n = 1)	10-tap (n = 2)	5-tap (n = 4)
Saturation slope (μrad/turn)	-41	-41	-38
Exponential time-constant (turns)	1098	1102	1111

CONCLUSION

Figures of merit defined on the transient and steady state dynamics of the beam have allowed a quantitative evaluation of the performance of the feedback system with various down sampling factors. These results show that for $n=2$ and $n=4$ down sampling has virtually no adverse effects on the beam transients or the steady state behavior. These results, together with the large savings in technical complexity of the hardware due to the reduced computational load on the DSP processors, suggest that down sampled processing is an important development for the practical implementation of the digital feedback system.

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