FAST DIGITAL DAMPERS FOR THE FERMILAB BOOSTER

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Abstract

As the intensity levels of the Fermilab Booster are pushed higher, it becomes necessary to have greater control over beam instabilities. One way to control these instabilities is with bunch-by-bunch active beam damping. This kind of damping imposes a very tight tolerance for the electrical delay from the detector to the deflector. The electrical delay must match the bunch revolution time, and the revolution time changes by 685ns in a period of 25ms in the booster. One way to track this delay is with a fast, time varying digital delay which is synchronized with the RF feedback system. A working prototype of a wide-band transverse digital damper system has been developed and tested on the Fermilab Booster. This paper will discuss the design, features, and results of the damper as well as problems associated with designing dampers for fast frequency sweeping accelerators.

I. INTRODUCTION

The upgrade of the Fermilab Linac from 200MeV to 400MeV has reduced the losses in the Booster due to space charge effects [1], but the increased beam current causes greater coupled bunch mode instabilities [2]. The challenges associated with designing a coupled bunch mode damper for the Booster are a large dynamic range, a fast sweeping RF system, and a large spread in tunes through the cycle. A digital system is ideal for handling these problems; therefore, digital bunched beam dampers were designed.

The damper configuration is shown in Figure 1. It consists of a common mode rejection front-end, digitizing units, fast memory, a D/A unit, and power amplifiers. All of the components, except for the power amplifiers, are VXI compatible and can be controlled with a personal computer or any other VXI control system. This paper will show why these functions are necessary to perform bunch-by-bunch damping in a fast sweeping accelerator and also show how the current Booster system satisfies these requirements.

II. DIGITIZERS AND MEMORY

Most of the problems associated with bunch-by-bunch damping in a fast sweeping accelerator can be addressed in the design of the digitizers and memory. The sampling process of the digitizers provides a natural rejection of the large common mode RF input signal. Delay and tune tracking can be implemented in the triggering and digital processing. A block diagram of the digitizer is shown in Figure 2.

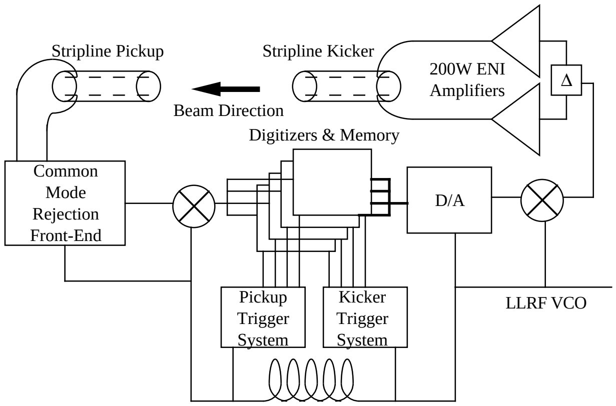

Figure 1: Block diagram of Fermilab Booster transverse digital damper system.

A. Components of Digitizer

The beam signal is mixed down with the RF frequency, filtered, and enters an A/D converter. The converter is triggered with a signal derived from the accelerator VCO

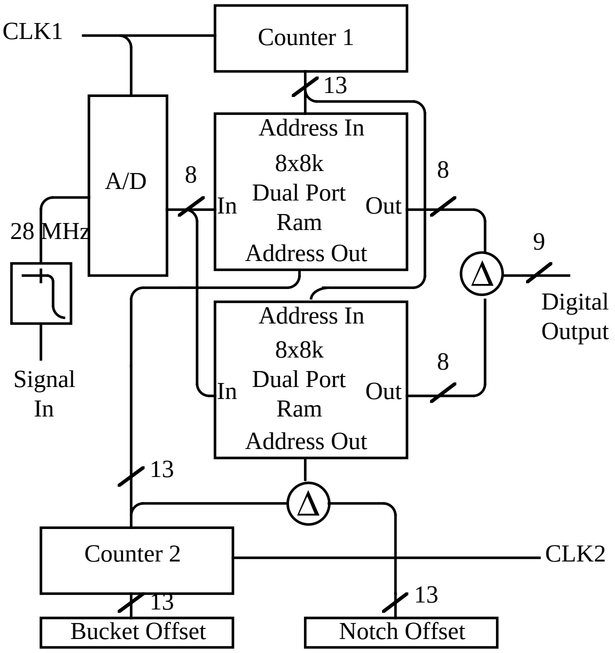

Figure 2: Block diagram of digitizer.

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*Operated by the University Research Association, Inc. under contract with the US Department of Energy.

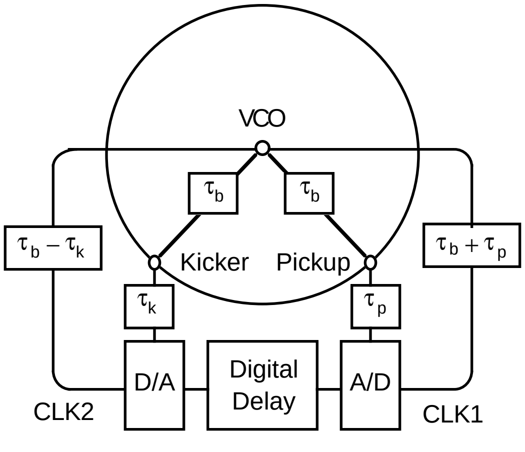
which remains locked to the frequency of the beam. This VCO signal drives a trigger system [3] which interleaves the digitizers according to the number of digitizers in the system and the number of beam occupied buckets in the accelerator. Although the A/D is capable of running at the RF frequency, the bit noise is significantly reduced by reducing the sampling rate.

From the converter, the data is stored in two fast dual port memories at the address specified by the top counter. The data is then output when the bottom counter matches the data's memory address. Counter 2 is set so that the combination of the delay in the memory plus the fixed cable delay is an integer number of beam revolutions, usually one revolution.

B. Delay Tracking

The RF accelerating voltage in the Booster must ramp from a frequency of 37MHz to 53MHz in a cycle time of 33ms, and the non-linear frequency ramp has a peak slope of 1GHz/s near the beginning of the cycle. The revolution period varies from 2.8µs to 1.59µs. To maintain feedback on the proper bucket, the processing system must handle 1.21µs of delay change quickly.

As long as the initial bucket delay is set correctly, taking into account beam velocity and fixed delay, the digital system will remain locked to the beam and provide proper bucket delay [4]. Figure 3 shows the timing conditions for the system. As the beam accelerates, more of the bucket delay is stored in the fixed cable delays, τ_p and τ_k. The bucket delay of the digital delay must be reduced. Because of the difference in delay from the VCO to the A/D trigger and the output trigger, an increase in frequency will trigger the output counter more than the A/D counter according to:



τ_b = Delay from VCO to Beam
τ_k = Delay from D/A to Kicker
τ_p = Delay from A/D to Pickup

Figure 3. Transverse Damper Timing Diagram.

$$\int_0^t f_{rf}[t' + \tau_k]dt' - \int_0^t f_{rf}[t' - \tau_p]dt' \tag{1}$$

The number of buckets stored in the fixed delay increases by the exact same amount so that the bucket delay stays matched.

C. Digitizer Common Mode Rejection

The output of the digitizers is the difference between the input delayed by the bucket delay and the input delayed by the notch delay. The response of this difference is given by:

$$H(\omega) = 2je^{-j\frac{n\omega}{2f_{rf}}} \sin(\frac{n\omega}{2f_{rf}}) \tag{2}$$

where n is the notch delay in number of buckets and frf is the accelerator VCO frequency. A plot of this response is shown in Figure 4 for n = h, the harmonic number of the accelerator. Notice that the amplitude response at the revolution frequencies is zero, and this will be true for a notch offset equal to any multiple of the harmonic number. Thus, this system reduces the output power requirements by eliminating the power due to unequal bunch population and low frequency synchrotron motion.

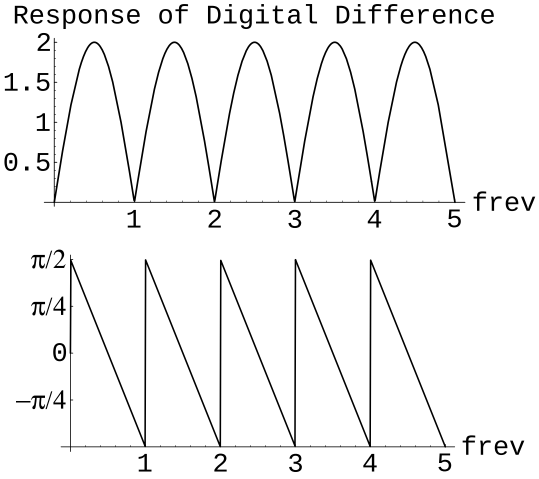


Figure 4: Response of the digital difference for n=h. The upper graph is the linear magnitude of the response and the lower graph is the phase in radians. The horizontal scale is in units of the revolution frequency.

D. Tune Tracking

Both the amplitude and phase responses of the system are important for good damper operation. One of the problems with the phase response of the system is the betatron phase advance from pickup to kicker. Ideally, this phase advance would be 90° [5], but due to physical limitations or changing tunes, this may not always be possible. Some dampers avoid this problem by having two pickups which are 90° apart in phase advance and summing the two signals with variable attenuators until the phase advance between the new signal and the kicker is 90°. The variable attenuators are controlled by a fixed program or feedback of some kind [6].

Another way around this problem is to use the phase properties of the notch filter itself. The difference between the betatron phase advance and 90° appears as a phase offset in the response of the damper system to the upper betatron sideband. The lower betatron sideband sees an equal but opposite phase offset [7]. The notch delay can be adjusted until the phase slope caused by the notch compensates for the difference in phase between the two sidebands. The notch delay has been designed to vary as a function of time in the cycle. It reads a look-up table which is programmed to follow the changing tune of the machine.

III. COMMON MODE REJECTION

The gain of a damper system determines the instability damping rate [8]. With the maximum output power fixed, the maximum gain of the damper is determined by the amount of undampable signal which saturates the power amplifiers. This signal includes noise, RF harmonics, rotation harmonics, and synchrotron motion (for a transverse system). The digitizing system will almost eliminate all these signals except for random noise, but these signals will still cause problems for the digitizer input. The Booster digitizers have 8-bits of precision, and a maximum input signal of 10dBm. This means that all signals above 10dBm saturate the digitizer, and all signals below -38dBm at the digitizer fall below the noise floor. It has limited dynamic range and acts as a large source of noise. There must be some kind of common mode rejection before the inputs to the digitizers.

A. Cable Matching

The Fermilab Booster uses a directional stripline pickup to detect the transverse error signal for the damper. The signals from the two plates (top and bottom for vertical; inner and outer for horizontal) are combined in a 180° hybrid. One way to reduce the common-mode signal is to match the delay and amplitude of each leg of the hybrid perfectly, moving the electrical center of the pick-up to the position of the beam closed orbit. Unfortunately, this will not track the beam as the closed orbit changes.

B. Down Conversion and AC Coupling

The fundamental RF signal is about 55dB greater than an undamped, stimulated betatron instability signal. By down-converting the signal and AC coupling, the fundamental RF can be eliminated, but the second harmonic of the fundamental is still 43dB greater than the stimulated instability signal. Some method of tracking the closed orbit of the beam must be devised to reduce the second harmonic of the fundamental RF frequency.

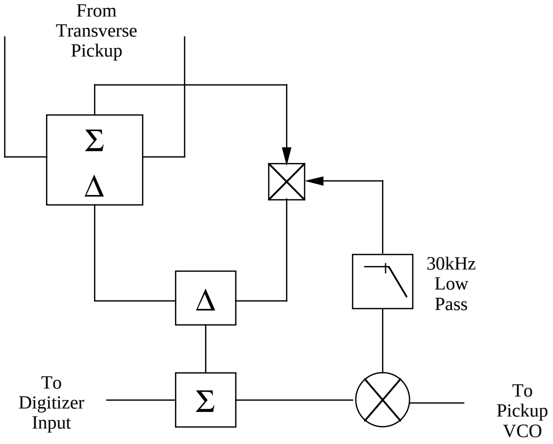


Figure 5: Booster transverse auto-zero circuit.

C. Closed Orbit Feedback

The method used for tracking the closed orbit in the Booster is shown in Figure 5. The signal from the hybrid is mixed down, amplified, and low-pass filtered. This filtered signal drives a fast, linear multiplier, and the other port of the multiplier is driven by the sum of the opposing plates. This multiplied sum signal is then subtracted from the hybrid signal to provide a tracking common-mode rejection. Signal associated with unequal bunch population is also reduced with this method since it effectively centers the beam between the plates. The only undesired signals it cannot reduce are longitudinal coupled bunch modes. These signals must be filtered by the digitizers.

D. Bandwidth Limiting

Information about all of the coupled bunch modes are contained in a bandwidth of half the RF frequency [9]. By limiting this bandwidth with filters, a majority of the aperture jitter noise that is inherent in the A/D converters can be reduced. A 28MHz low-pass filter is used just before the input to the digitizer to reduce the noise as well as help reduce the second harmonic of the fundamental RF.

IV. D/A AND AMPLIFIERS

The outputs of the digitizers are connected to the D/A through a 9-bit bus line. The kicker trigger system mediates the bus while the D/A triggers at the RF frequency. A block diagram of the D/A system is shown in Figure 6. The data from the bus enters a dual port RAM look-up table. This look-up table has many pages and is used to provide a digital gain coefficient for the system. After the table, the signal enters a 10-bit D/A converter. The signal from the converter is filtered to reduce overshoot noise and upconverted for a better response to the hybrid and amplifiers.

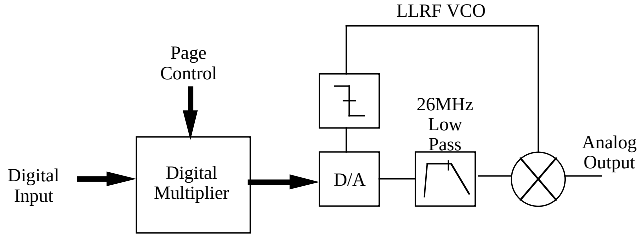


Figure 6: D/A block diagram.

The upconverted signal is split with a 180° hybrid and is then input in to two 200W ENI amplifiers. The amplifiers' bandwidth ranges from 100kHz to 150MHz and the electrical delays of these amplifiers are matched to better than 1ns. Each amplifier drives one plate of a stripline kicker to complete the circuit.

V. SYSTEM CONTROL

All of the components for the Booster damper system, except for the power amplifiers, are VXI compatible. This system uses a Macintosh computer with a National Instruments VXI-NuBus adapter and LabView® software for control . The control system is capable of adjusting the phase of the RF for upconverting and downconverting, adjusting the synchronization and patterns of the trigger systems, changing bucket and notch delays, and reading from and writing to the digitizer memory. Given only the information about the number of buckets and bunches in the machine and the desired bucket and notch delays, the computer is capable of setting all the components for effective damping. Once the system has been configured for damping, it can run independently from the computer. The computer can also be used to program the system for many different configurations. Examples are read only mode for measuring instabilities, write only mode for resonating a betatron instability, and transfer function measurement mode for measuring the system response.

VI. SYSTEM RESPONSE

A simplified diagram of the closed loop damper response is shown in Figure 7. The formula for this response is:

$$\frac{R(s)}{N(s)} = \frac{G(s)}{1-H(s)G(s)} \tag{3}$$

As long as the real part of H(s)G(s) remains less than +1, the system will be stable for all frequencies [10]. One way to check the response of the system is to measure the H(s)G(s) product directly by opening the feedback path, stimulating the beam, and measuring the damper output.

The most common way for measuring the H(s)G(s) product for a fixed frequency synchrotron is to place a network analyzer between the output of the low level damper system and the power amplifiers. It can be difficult to locate the frequencies where the beam has a detectable response because the beam can have a very high Q at the betatron frequencies. However, once the response is located at two frequencies, the remaining betatron responses are very easy to locate because they must differ by an integral multiple of the revolution frequency.

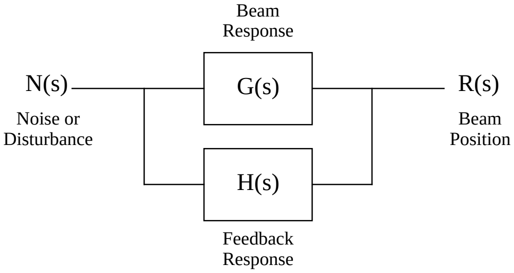


Figure 7: Block diagram of closed loop response for a damper system.

If the frequency of the synchrotron is not fixed, it becomes impossible to measure the response of the H(s)G(s) product with a network analyzer. The revolution frequency will change significantly during the time it takes to resolve the betatron response causing a smearing of the response. For a sweeping frequency, it is better to use the digital damper system itself for making the transfer function measurements. The digitizer memories can be loaded with a sine-wave pattern and played on to the beam. While the pattern is being played, the system can be storing the response from the pickup right behind it. Once all the memory has been played, the response is compared to the stimulus pattern with the proper compensation for the system delay. Figure 8 shows a response measurement of many betatron modes. Since the system tracks the changing delay, the only way the signal will look smeared is if the tune changes significantly during the

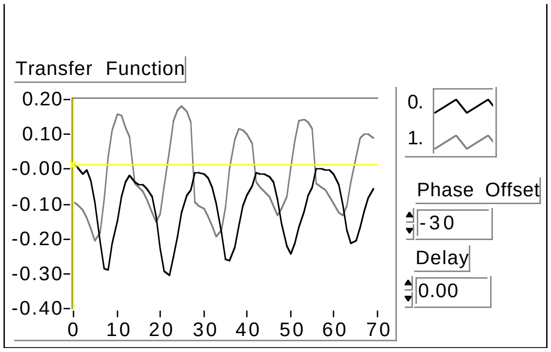


Figure 8: Plot of response measurement for many betatron modes. This plot shows modes 0, 1, 2, 3, and 5. The vertical axis shows the linear value of the real and imaginary response, and the horizontal axis shows the number of data points. The delay and phase offset are adjusted for most negative real response.

measurement. With the ability to measure the response of the system, the bucket delays and notch delays can be tuned for damping throughout the entire Booster cycle.

VII. RESULTS OF DAMPER SYSTEM

The Fermilab Booster currently has one operational horizontal damper system. Although the system has the proper phase response through the entire cycle, the beam does not have any horizontal instabilities above the noise floor at the beginning of the cycle. The dampers do, however, have a profound effect on instabilities at the end of the cycle. Figure 9 shows a comparison between dampers on and dampers off for beam which is kicked horizontally during the last half of the Booster cycle. A vertical system is under construction and should be operational very soon.

VIII. ACKNOWLEDGMENTS

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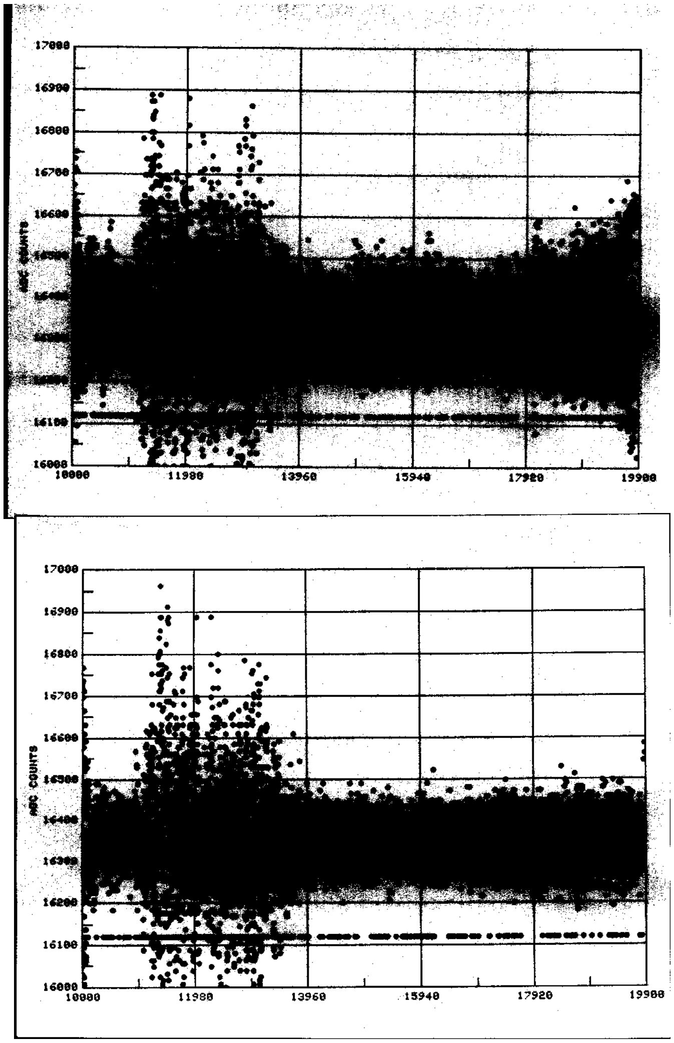

Figure 9: Plots of turn-by-turn horizontal position of Booster beam for the last half of the cycle. The top plot shows data with the dampers off, and the bottom plot shows data with the dampers on. The noise at the beginning of the plot is caused by synchrotron oscillations.