DIGITAL TRANSVERSE BEAM DAMPERS FOR THE BROOKHAVEN AGS*

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ABSTRACT

A wide band, digital damper system has been developed and is in use at the Brookhaven Alternating Gradient Synchrotron (AGS). The system consists of vertical and horizontal capacitive pickups, analog and digital processing electronics, four 500 Watt wide band power amplifiers, and two pairs of strip line beam kickers. The system is currently used to damp transverse coherent instabilities and injection errors, in both planes, for protons and all species of heavy ions. This paper discusses the system design and operation, particularly with regard to stabilization of the high intensity proton beam. The analog and digital signal processing techniques used to achieve optimum results are discussed. Operational data showing the effect of the damping is presented.

INTRODUCTION

As the AGS moves towards its intensity goal of 60 Tp per cycle, there is an increasing need to reduce the effects of injection errors and transverse coherent instabilities that cause beam loss during acceleration. Active feedback systems, called beam dampers, designed to reduce these effects, have been installed in both the vertical and horizontal planes and are now being used to maintain beam stability. This system functions by measuring the position of each beam bunch at one point in the ring and calculating a correction signal which it applies as the same bunch passes a strip line deflector located nearly one turn, or 2.5 usecs later.

A previous paper presented a broad view of the AGS damper[1], here the system will only be presented in summary. The focus of this paper is the design and operation of the digital processing architecture and data is shown demonstrating its effectiveness.

SYSTEM DESCRIPTION

A block diagram of one plane of the AGS Damper system is shown in figure 1. It is a wide band, bunch by bunch system with a bandwidth of 20 kHz to 5 Mhz. Beam bunch position is obtained from pairs of capacitive pick up electrodes (PUE) located in the downstream end of the F20 straight section. The 20 to 50 nsec bunch signals (frequency from 3 to 4 Mhz) go to high impedance preamplifiers less than 10 feet from the PUE's. The

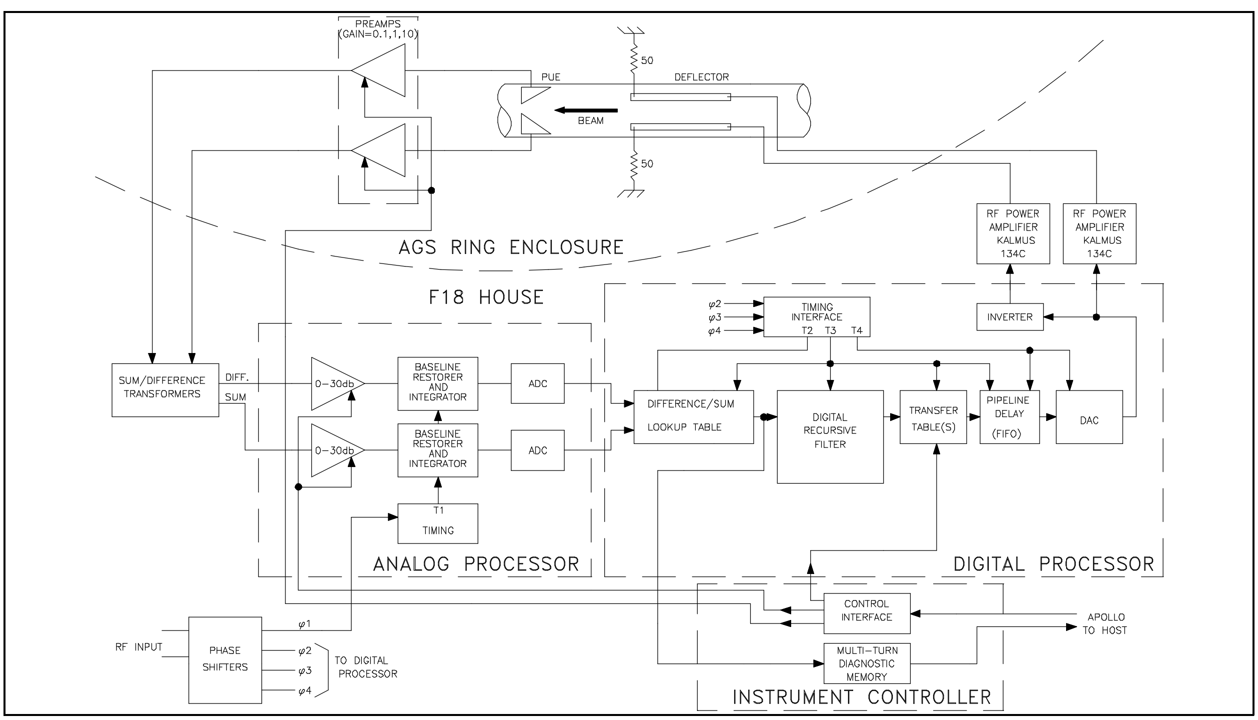

Figure 1 - Block diagram of one plane of the AGS Damper System

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amplifiers have gains of 10, 1, or 1/10 and impedance match the pulses to 50 Ohm semi-rigid coax that goes to electronics in one of the service buildings in the center of the AGS ring. Hybrid transformers form the sum and difference before the signals go to the analog processor.

In the analog processor, variable gain buffer amplifiers boost the signals another 0 to 30 db before the bunch signals have their base lines restored. This adds back the zero level of the signal lost in the capacitive coupling of the pick up by sampling the input between bunches. Sampling during this interval is done using a clock signal that is locked in frequency and phase with the beam through the entire cycle.

Next, each bunch signal is integrated for one RF clock cycle and the resulting voltage digitized by fast, 8 bit ADC's. Integration is necessary to obtain a centroid that is independent of bunch shape. The integrators used were originally developed for the AGS Booster Damping system[2]. They multiplex two internal integrating channels allowing one full RF period for the result to be acquired and the integrator to be reset.

The digitized sum and difference signals are the inputs of the digital processor. Data is indexed through the system by phased clock signals which are derived from the same source as the BLR clock. A programmable read only memory (PROM), acting as a look up table, generates difference divided by sum. This quotient, which represents the transverse bunch position, is output to a gate array programmed to implement a recursive transfer function using the algorithm discussed below[3][4]. In addition, the quotient is sent to an external memory. This memory is currently capable of storing 16000 turns of bunch data.

Finally, another PROM acts as a final correction signal look-up table. This table contains multiple pages of different transfer functions that can be selected remotely or by specific time events. This transfer tables provide for simple selection of digital gain and dead band options. Several inverse options in this table allow the system to be converted to anti-damping modes so that proper timing can easily be verified. Under the proper conditions the damper in these modes can function as a tune kicker.

Since the signal processing takes less than a revolution period a delay is needed for the correction value before it can be output. This delay is accomplished using a first-in, first-out (FIFO) memory. The FIFO is initialized with blank input bytes prior to strobing in the first data byte. This establishes a ripple through delay, in clock pulses, of input to output. The elegance of using a FIFO for this delay is that phase and frequency of the input and output data are independent.

In the final step the correction value is clocked into an eight bit analog to digital converter (DAC). The resulting analog signal is amplified by 500 Watt RF power amplifiers and applied to 50 Ohm strip line kickers at just the moment that the bunch reaches the strip lines.

THE DIGITAL PROCESSING ALGORITHMS

As the eight bunches circulate in the AGS, coherent motion of their centroids seen at a fixed point describes an ellipse in phase space in each plane, given by the Courant-Snyder invariant:

$$\varepsilon = \pi(\gamma x^2 + 2\alpha x x' + \beta x'^2)$$

where x and x' are the position and angle of the bunch as it passes a point along the orbit and ε is the beam emittance.

The purpose of the damper is to reduce ε. It can do so only by applying a kick (i.e. an angular deflection) to the bunch. The basic problem for the processing algorithm is to determine, for each bunch, the best magnitude and sign for a kick, given the PUE position measurements from one or more previous turns. One difficulty is that the measured positions contain closed orbit beam offsets as well as the coherent motion to be damped. Some filtering is needed to prevent the damper from attempting to correct this slowly changing closed orbit.

A recursive filter algorithm (IIR) has been chosen which acts as a high-pass filter. The recursive nature of the filter allows for the economical inclusion of a very large number of previous turns in determining the value of the constant closed orbit information.

The algorithm chosen implements the following finite difference equation:

$$y(n) - (1-k)y(n-1) = x(n) - x(n-1)$$

where *x(n)* is the digitized beam position measurement on turn *n* and *y(n)* is the output correction. Figure 2 shows a flow graph of the filter which is implemented in a programmable gate array.

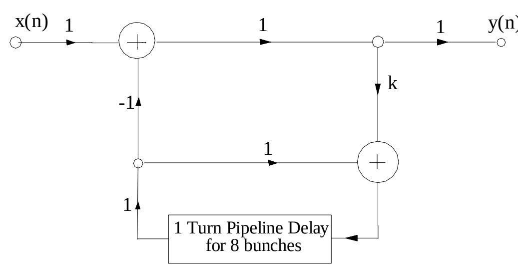

Figure 2 - Flow graph of the recursive filter algorithm with the 8 bunch pipeline delay

The transfer function of this filter for each bunch is:

$$H(z) = \frac{1 - z^{-1}}{1 - (1-k)z^{-1}}$$

The value of k (k<1) determines the low frequency cutoff. Smaller values of k push the cutoff frequency toward zero. In the AGS Digital damper this value is implemented by a shift register (divide by 2^n) with a choice of n =0,1,2 or 3.

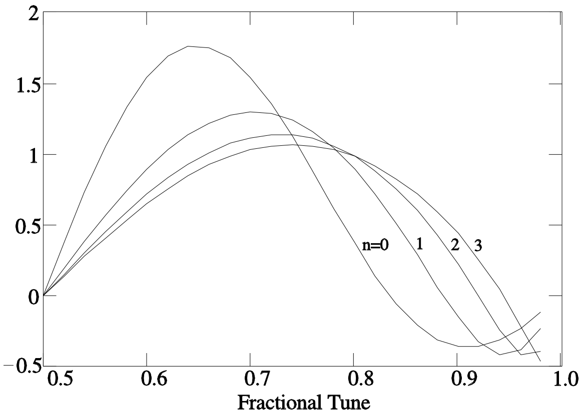

Figure 3 - Effect of the damper in reducing emittance as a function of tune for n = 0,1,2 and 3 using the PUE at F20.

In the AGS Damper, position data can be taken each revolution from either of two PUEs (in sections F20 or G7). The kick is applied at F20 on the turn following the position measurement. An analysis of the effectiveness of a kick in reducing ε shows that sensing and kicking at F20 favors fractional tunes close to 0.75, moving the sensing PUE 60^{O} in betatron phase to G7 still produces a net reduction but favors higher fractional tunes[4]. Figure 3 shows the relative effect of the damper with the recursive filter in reducing beam emittance for n = 0,1,2 and 3 with the pick-up (PUE) at F20. Choosing larger values of n permits effective damping to extend to higher tunes and still obtain good closed orbit subtraction.

Following the filter is an additional lookup table referred to as the transfer table. This PROM contains up to 15 user selected ways to condition values of y(n) before actually applying them to the output. These functions are used to provide different digital output gains, inversion to cause anti-damping or dead bands of various widths to filter noise.

THE DIAGNOSTIC MEMORY

One benefit of digitizing signals is that they may then be easily stored. One important adjunct to the digital damper system is the capacity to store up to 16,000 turns of position data in both horizontal and vertical planes, triggered by a time event. High level software then parses the data by bunch and can display it or save it for later analysis. While this "diagnostic memory" plays no part in actually damping the beam, it has proved to be an indispensable tool in the ongoing attempt to understand the AGS and in studying the effect of the dampers.

RESULTS

As the AGS has achieved intensities of 60 Tp and higher, the transverse dampers, especially in the vertical plane, have played a critical role. Data showing the effect of the dampers has been elusive however, simply because the occurrence of instabilities is not very predictable cycle to cycle. One technique that has brought good results uses the AGS Tune Meter Kicker to create some coherence and records with the diagnostic memory the change with damping off and on. Figure 4 shows the results in the vertical plane early in the AGS cycle. In the

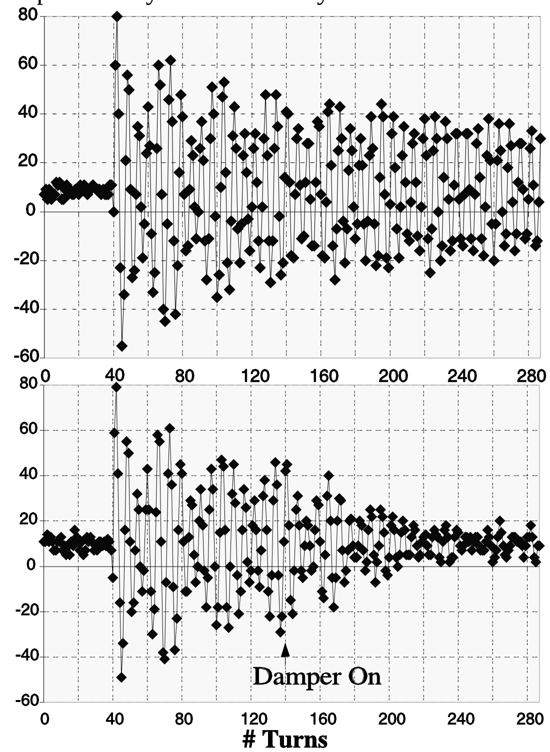

Figure 4 - Effect of damping on the coherence caused by the tune kicker (a) No damping, (b)Damping on 100 turns after tune kick

upper graph, the damper is off. In the lower graph, the damper is gated on at about 300 usecs or 100 turns after the tune kick. Within 100 turns of turn on the coherence caused by the kick is dramatically reduced.

REFERENCES

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