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# Overview of Coupled Bunch Active Damper Systems at FNAL

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**Abstract**. Beam intensities in all of the accelerators at Fermilab will increase significantly when the Main Injector becomes operational and will cause unstable oscillations in transverse position and energy. Places where the coupled bunch oscillations could dilute emmitances include the Boosters Main Injector, and Tevatron. This paper provides an overview of the active feedback system upgrades which will be used to counteract the problem. It will explain the similarities between all the systems and will also explain design differences between longitudinal and transverse systems, fast sweeping systems, and systems for partially filled machines. Results from operational systems will also be shown.

## INTRODUCTION

The accelerators at Fermilab provide a wide range of challenges for designing and constructing beam feedback systems. The basic concept of any beam feedback mechanism involves detecting an error in position, time, or energy of a bunch at the pickup, processing this signal and holding it until the bunch arrives at the kicker for correction. Challenges in the design of the system include dealing with the large dynamic range of the pickup signal, maintaining the proper timing and phase advance from pickup to kicker, providing a large enough kick to the bunch, and providing a means to diagnose mismatches in delay and phase as accelerator parameters are tuned.

The following table illustrates the differences between the three accelerator rings at Fermilab. In particular, one should note the total change in acceleration voltage frequency, which determines the total change in delay from pickup to kicker, and also note the percentage of buckets filled, which determines the kind of front end processing required. All of the rings have or will have coupled bunch dampers for every plane. The rest of this paper discusses the similarities and differences between damper systems for different planes and different machines.

Table 1

## TRANSVERSE DAMPERS

Construction of transverse dampers is not as costly as longitudinal dampers because the gain of the system does not need to be as high (1). Consequently, the power amplifiers used to drive the kickers have lower power requirements, and the kickers can have a much wider bandwidth. Because the bandwidth of the system can be so great without extraordinary cost in power amplifiers, most transverse systems are designed to handle all possible coupled bunch modes. Figure I shows a block diagram of the transverse damper system that is used or will be used in all of the accelerators. All of the systems include a stripline pickup and kicker, an analog front end/auto-zero, a digital notch filter, and a wideband power amplifier. The only differences between the systems for the different accelerators are the bandwidth of the stripline components, the bandwidth and processing of the analog front end, the trigger generation for the digitizers, and the power capabilities of the power amplifiers.

Figure 1

## Stripline Components

The specifications of the stripline length are not critical for the damper system. The pickup stripline needs to be short enough to have a passband as wide as the value of the RF frequency, but it must be long enough not to have too much attenuation at the operating frequency of the damper. All of the current transverse dampers operate at the RF frequency. The quarter-wave frequencies of the Booster, Main Ring, and Tevatron pickups are 120MHz, 212MHz, and 53MHz respectively. The pickups can be short in this case because the signal is so large. Even at the RF frequency, the signal from the pickup is attenuated to accommodate the maximum input level of the analog front end. The quarter-wave frequencies of the stripline kickers for the Booster, Main Ring, and Tevatron are 75MHz, 75MHz, and 53MHz respectively.

## Analog Front End / Auto-Zero

Signals due to betatron motion of the beam are at least 60dB down from the fundamental signal in the Fermilab accelerators. No digitizer has the combination of speed and dynamic range to process the signal directly, so an analog circuit was designed to enhance the betatron signal (2). The circuit enhances the betatron signal by creating a virtual electrical center in the pickup which tracks slow variations in beam position while passing variations in beam position associated with betatron motion. This technique will stop signal due to closed orbit error, bunch-to-bunch intensity variations, and mode-0 synchrotron motion at high dispersion.

Figure 2 shows a block diagram of the system. The signals from the two sides of the stripline pickup are input into a 0°/180° hybrid. From the hybrid, the sum and difference signal are filtered with matched filters, attenuated, and input

Figure 2

into a pair of linear analog multipliers. The difference between the two products gives the difference signal with the electrical center displaced. Tracking is provided by the other factors on the multipliers which are derived from the input signals in the feedforward case or the final difference signal in the feedback case. The method used to derive the tracking signal varies with accelerator parameters.

### *Tracking with Every Bucket Filled*

Every bucket in the Fermilab Booster ring is full during acceleration. The dominant signals, from an uncompensated pickup, are due to the fundamental RF and harmonics of the RF. The tracking for the multipliers can be derived by mixing the error signals with the fundamental RF frequency and low-pass filtering the signals just above the maximum synchrotron frequency. If phase errors between the sum and difference legs of the system cause insufficient rejection of the higher harmonics of the RF, extra feedback multipliers can be added which cancel out only the higher harmonics.

### *Tracking in a Partially Filled Machine*

The reference (2) listed in the back of this paper explains the details of the auto-zero circuit for a partially filled machine. It is important to realize that the mixers used to derive the tracking signal for the full machine will not work as well for the partially filled machine because the beam spectrum will be more evenly distributed among the revolution harmonics. Thus, it is better to use sample and holds, which can track a single bunch, in place of the mixers.

## Digital Processing

The purpose of the digital processing is to provide the proper delay and phase shift at all of the betatron coupled bunch frequencies to damp all of the modes. It also notches out any remaining common mode signal from the auto-zero circuit, as well as notching out any signal due to coupled bunch synchrotron oscillations which the auto-zero circuit cannot detect. The digital processing circuit also acts as an advanced damper diagnostic tool capable of measuring beam spectrums and beam transfer functions.

After the auto-zero circuit, the difference signal is mixed down to baseband, anti-alias filtered, amplified, and sent to the digitizers. The digital processing consists of from three to seven interleaved 8-bit digitizers with dual port memories and two trigger systems to control the digitizers. One trigger system controls the sampling time of all the digitizers, while the other trigger system controls the output data latch of the digitizers. The trigger systems are referenced to the accelerator voltage controlled oscillator with different delays, and each of the trigger systems can operate asynchronously with respect to one another. With the delays set properly, the system will maintain the proper timing from pickup to kicker, even if the revolution frequency of the beam varies rapidly (3).

The digitizers also contain an adjustable notch filter which controls the phase shift on the betatron lines to compensate for the phase advance from pickup to kicker. This filter's properties can be changed as a function of time in the acceleration cycle in order to track changes in phase advance due to changes in tune.

Output data from the digitizer cards are bussed to a D/A card which contains a dual port look-up table for adjusting digital gain and a 10-bit DAC. The output of the DAC is then sent to the power amplifiers.

### *Timing Considerations for Large Radius Accelerators*

The digitizers, trigger systems, and DAC rely on the accelerator reference oscillator to remain synchronous with the beam. The reference oscillator must adjust its frequency prior to a change in beam velocity in order for the triggers to remain synchronous. The lead time of the oscillator is determined by the electrical delay from the oscillator to the accelerator cavity. If the electrical delay from the oscillator to the digitizers exceeds this lead time by an amount on the order of the total change in oscillator frequency, synchronization will be lost.

In the case of the Tevatron, the total change in oscillator frequency is so small that the oscillator signal can be distributed anywhere in the ring without significant phase slippage. The Booster, on the other hand, has an extremely large frequency sweep, but the lead delay of the oscillator is about one revolution period. This means the oscillator signal can be distributed anywhere in the

Booster ahead of the lead time, making it possible to synchronize the digitizers through the cycle.

The Main Ring and Main Injector have significant frequency sweeps, short lead delays, and large radii. When the oscillator signal is cabled to the other side of the ring, the phase slips more than five full buckets relative to beam through the acceleration cycle. This causes a delay error on the damper system of more than 10 buckets which is unacceptable. Therefore, an RF phase unwinder system was designed and built for use by the Main Ring and Main Injector dampers (4).

## Results and Measurements

The Booster digital transverse dampers have been in operation for over a year. Detailed results and analysis of the Booster dampers can be found in the reference listed at the end (5). The Booster system has also been programmed to function as a tracking network analyzer for measuring beam transfer functions. The methods used for the measurement and the results are also shown in the reference.

Using the damper system is an ideal way to measure transfer functions in a fast frequency sweeping machine, because commercial analyzers cannot lock to

Figure 3. Comparisons of noise spectrums from Tevatron damper input. Top graph is horizontal and bottom graph is vertical. Smooth traces are with dampers off, and traces with valleys are with dampers on.

the reference frequency. However, the resolution of the system is limited by the amount of memory. For relatively fixed frequency machines, such as the Tevatron, it is more advantageous to use commercial analyzers and take advantage of the finer resolution. Figure 3 shows the spectrum of the Tevatron dampers using a vector signal analyzer with the feedback loop open and closed. The noise spectral density of the damper at the betatron frequency is reduced by the squared ratio of the damping time over the decoherence time when the loop is closed (6). The plot shows that the horizontal Tevatron dampers have a damping rate of about three times the decoherence rate.

## LONGITUDINAL DAMPERS

Longitudinal impedances are usually much greater than transverse impedances which cause an equal growth rate. Therefore, the gain of longitudinal systems will be greater and require more voltage on the kicker than a transverse system. For example, the electronic gain of the longitudinal system needs to be better than 70dB in the Booster just to counteract instability growth rates (7). Calculations show that, to have dampers which damp injection oscillations in the Tevatron on

Figure 4. Block Diagram of Narrowband Longitudinal Damper Low Level.

the order of 10 synchrotron periods, it would require 10kV on the kicker. This corresponds to lMW of power into a wideband 50Ω cavity, and it would be extremely expensive to build. Therefore, the longitudinal dampers are primarily narrowband, high impedance systems.

## Narrowband Systems

Narrowband damper systems concentrate on one or a small number of coupled bunch modes. Figure 4 shows a block diagram of a single mode, longitudinal, coupled bunch damper (3). The direct digital synthesizer (DDS) keeps the reference frequency of the circuit locked to the frequency of the coupled bunch mode. The band pass filter is configured so that the dipole motion synchrotron frequency passes with a 90° phase shift while DC and frequencies well above the synchrotron frequency are filtered out. The bandwidth of the signal after the filter is on the order of a few kHz or smaller, so errors in delay from pickup to kicker look like a phase shift at the coupled bunch mode frequency. A phase shifter is added just before the power amplifiers to compensate for delay errors which may change as a function of time in the cycle. The Booster currently has narrowband dampers working on coupled bunch modes l, 49, 50, and 5l after transition. Because these dampers operate after transition, the maximum synchrotron frequency is limited to 2kHz. This makes the design of the analog bandpass filter easier, reducing the chances of driving higher order modes with the system. The damper uses the power amplifiers and cavities of the acceleration system as its final amplifier and kicker. This saves a great amount of time and money, because there is no need to design and purchase a specialized, high voltage amplifier and cavity. Unfortunately, this technique only works where the amplifiers have a good response and the cavities have a high impedance. In the case of the Booster, the first mode is close enough to resonance to have a high impedance, and the other modes correspond to a parasitic resonance in the cavity.

## Wideband Systems

It is quite easy to convert a digital transverse system into a longitudinal system by changing the analog front end to look at phase deviations instead of amplitude variations and by running the stripline kicker in common mode instead of differential mode. Again, the amount of power required to damp injection oscillations would be inhibiting. If, however, there are some or many slow growing instabilities that need to be controlled, the digital system could be a viable solution depending on the beam intensities and the instability growth rates.

Another application for the longitudinal wideband system is in a partially filled accelerator with bunches evenly spaced. In the Tevatron during colliding mode, there will be 36 proton bunches, spaced almost evenly around the ring. In this case, the bandwidth of the system is greatly reduced, and it is again possible to use the accelerating amplifiers and cavities to damp the beam. A digital, wideband, longitudinal damper system which uses the accelerating cavities is currently being designed for the Tevatron.

## REFERENCES


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**TABLE 1.** Fermilab Accelerator Parameters

| Ring | Energy | RF Frequency | RF Buckets | Bunches |
|---|---|---|---|---|
| Booster | .4 - 8 GeV | 37-52.8 MHz | 84 | 84[a] |
| Main Ring[b] | 8-150 GeV | 52.8-53.1 MHz | 1113 | 1,12,84 |
| Main Ring[c] | 8-150 GeV | 52.8-53.1 MHz | 1113 | 1092 |
| Main Inj[b] | 8-150 GeV | 52.8-53.1 MHz | 588 | 1,12,84 |
| Main Inj[c] | 8-150 GeV | 52.8-53.1 MHz | 588 | 504 |
| Tevatron[b] | 150-1000 GeV | 53.1 MHz | 1113 | 1 - 36 |
| Tevatron[c] | 150-1000 GeV | 53.1 MHz | 1113 | 1092 |

[a]Booster may have a one bucket gap for firing the extraction kickers.
[b]Collider Mode: Main Ring/Inj is used for coalescing and stacking.
[c]Fixed Target Mode: Machines are full.

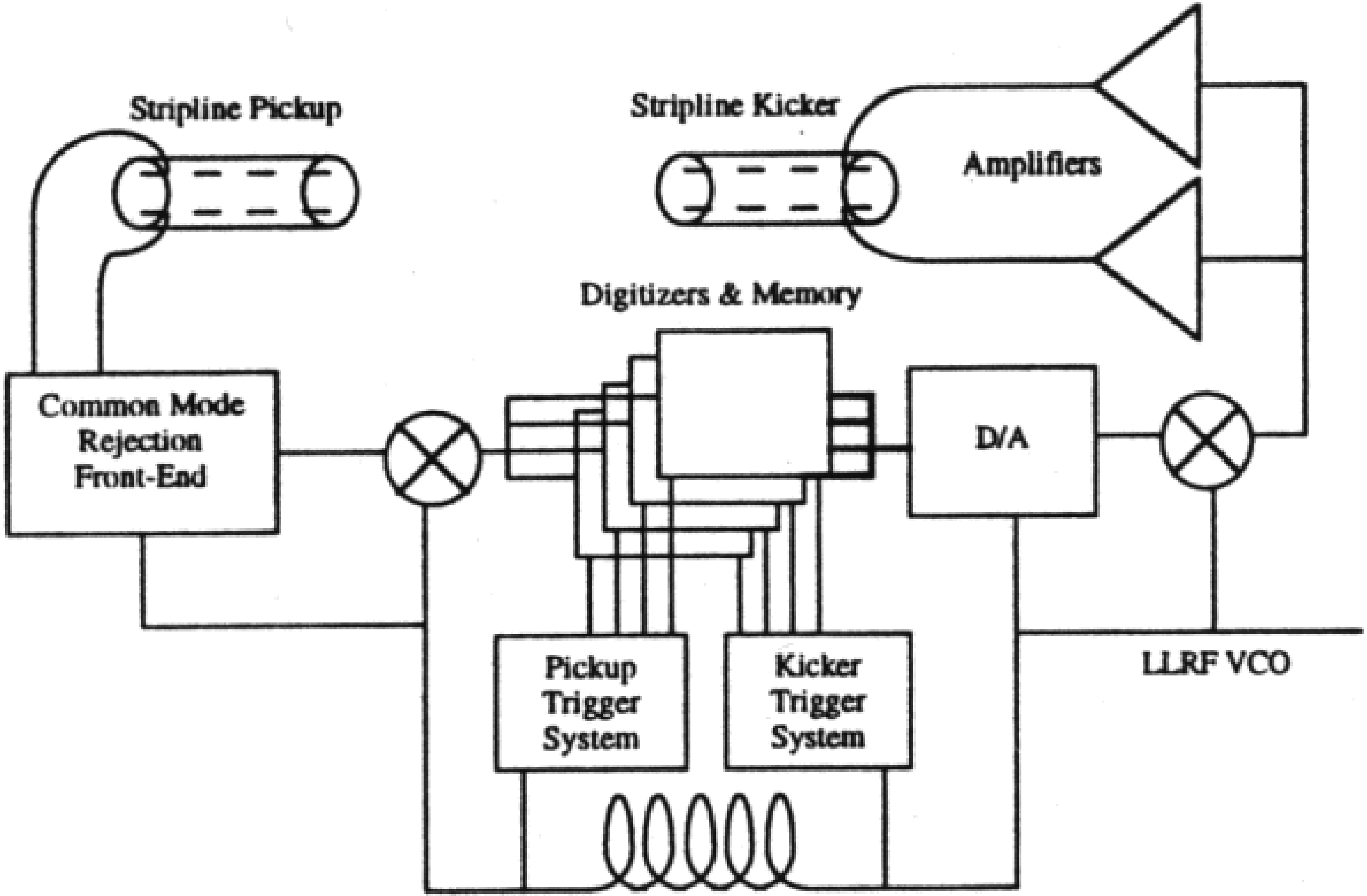



**Figure 1.** Transverse Damper Block Diagram

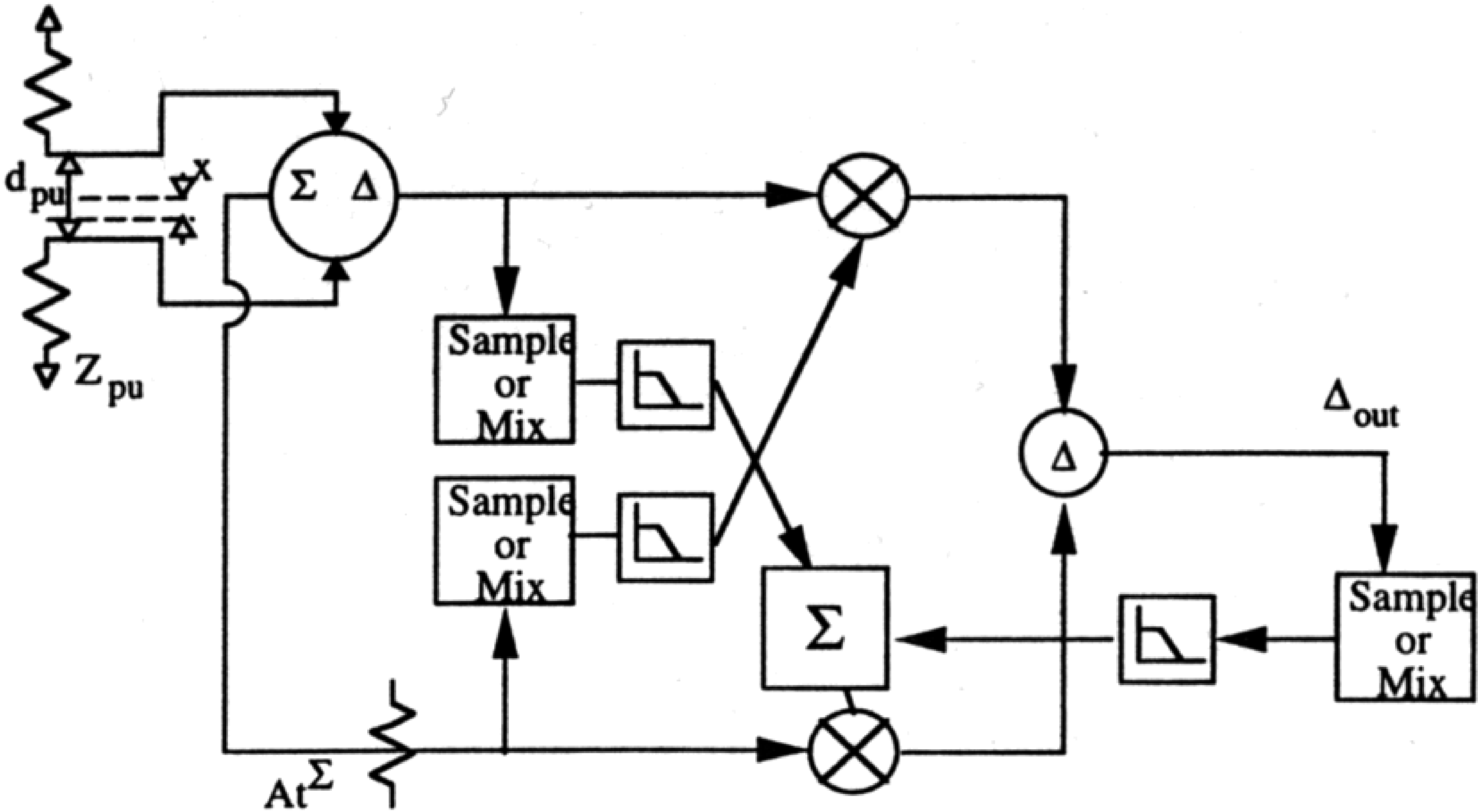
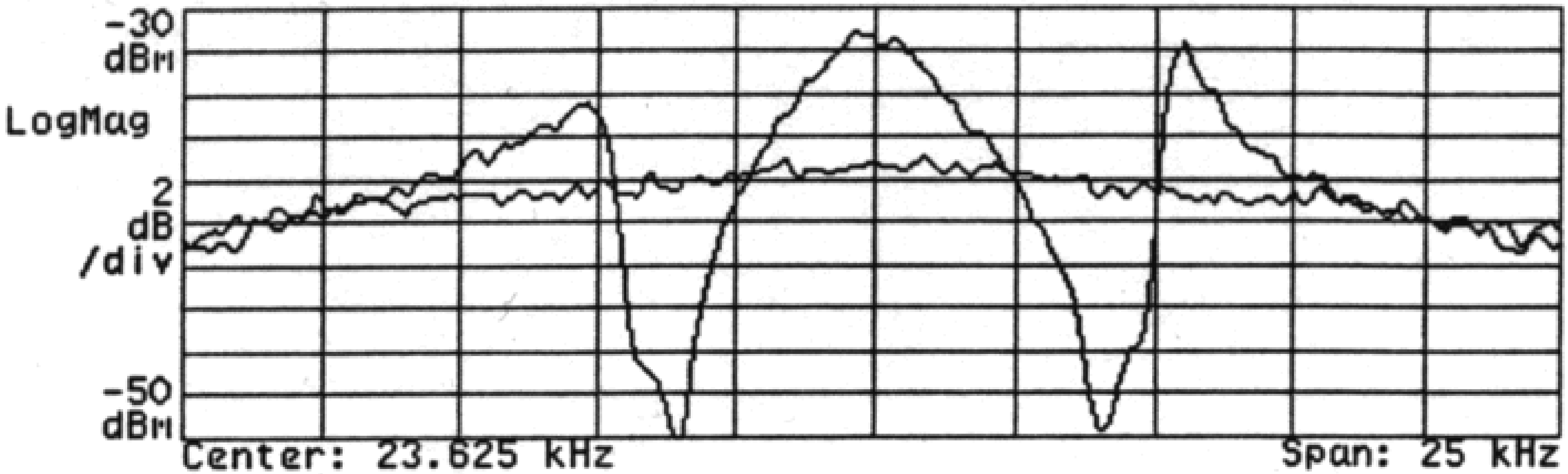
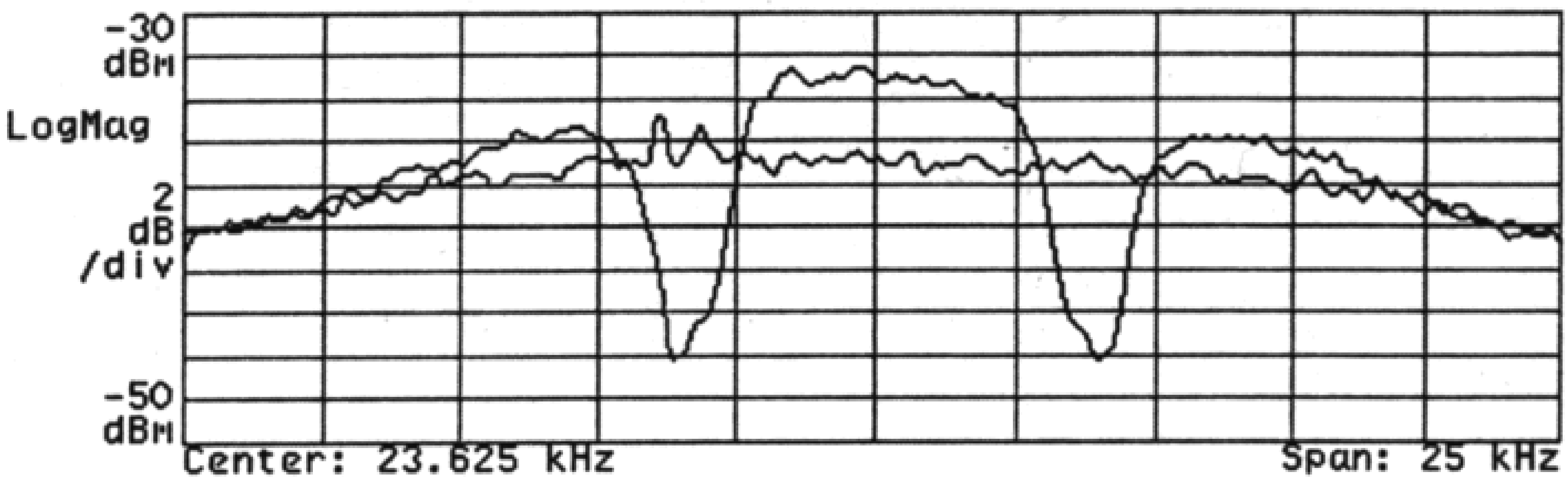



**Figure 2.** Auto-Zero Block Diagram.

TRACE A: D1 Spectrum




TRACE B: D2 Spectrum



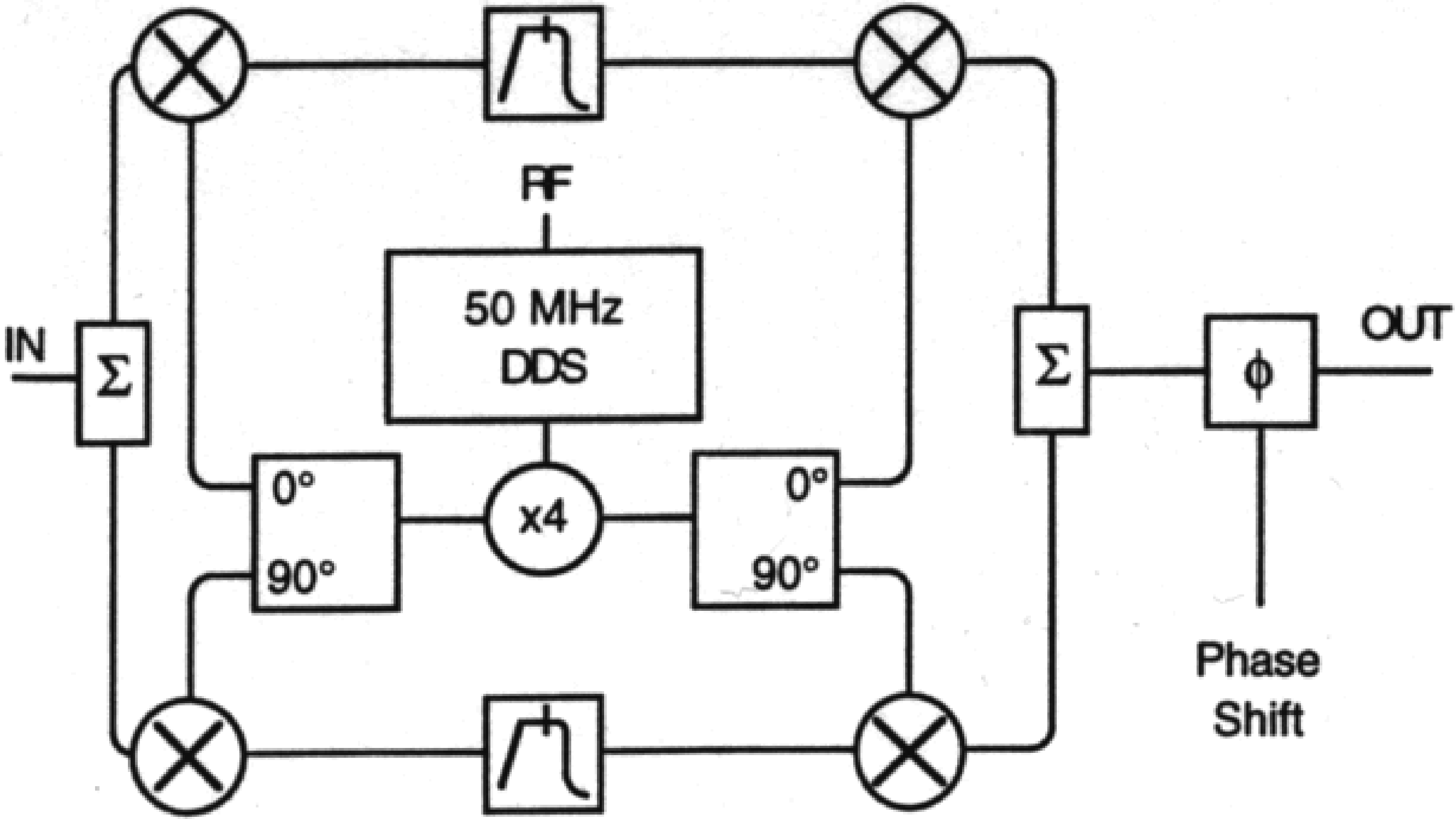



**Figure 4.** Block Diagram of Narrowband Longitudinal Damper Low Level.