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ADAPTIVE CONTROL TECHNIQUE FOR ACCELERATORS USING DIGITAL SIGNAL PROCESSING*

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The use of present Digital Signal Processing (DSP) techniques can drastically reduce the residual rf amplitude and phase error in an accelerating rf cavity. Accelerator beam loading contributes greatly to this residual error, and the low-level rf field control loops cannot completely absorb the fast transient of the error. A feedforward technique using DSP is required to maintain the very stringent rf field amplitude and phase specifications.

Introduction

This paper presents a concept for using Digital Signal Processing (DSP) techniques and technology to solve a control problem in a Neutral Particle Beam (NPB) accelerator. Specifically, the problem is to control the rf amplitude and phase in an accelerating cavity for the NPB accelerator. DSP techniques become very useful for adapting to both a research environment and to the long-term operational aspects of an accelerator. This paper discusses DSP techniques that help to control the rf cavity fields. A brief explanation of the accelerator control application is given for background.

Typically, rf field control for accelerating cavities is implemented with high-speed analog circuitry. The limiting factor in the control bandwidth is the pole configuration of the cavity. An adaptive control loop is necessary because the cavity's thermal and mechanical characteristics prevent the poles from remaining stationary.

When the accelerated particle beam enters a cavity that is filled with rf energy, a beam-loading effect transfers energy present in the rf to the beam, thus causing the particles to accelerate. The role of the rf control circuitry is to keep the rf field's phase and amplitude constant while the cavity is being filled with rf energy, when the beam enters the cavity and while it is present. This control is accomplished satisfactorily during steady state but not during the initial loop transient, thus causing a residual loop error in both phase and amplitude.

An accelerator operates in a repetitive mode; therefore, conventional feedforward techniques can help to reduce systematic errors. However, a practical feedforward system can only cope with a limited number of stimuli, and its implementation is limited in accuracy. In a typical control loop several sources of loop perturbations exist, such as component nonlinearities, klystron anode voltage droop, and amplitude/phase cross coupling. To aggravate matters, these perturbations vary with time and component aging. Mechanical and thermal changes in the cavity structure cause the characteristic resonance of the cavity to vary as well. DSP technology can adapt to these changes by constantly monitoring the residual error signal and can inject the correction signal after processing and filtering the error. This paper will describe this technique applied to the NPB accelerator at Los Alamos.

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Application Description

Figure 1 shows a basic block diagram of the NPB accelerator with the emphasis on the rf drive sections. An injector starts ions first into the radio-frequency quadrupole (RFQ) cavity. This cavity helps with the bunching of the particles and adding energy. The Ramped Gradient Drift-Tube Linac (RGDTL) and drift-tube linac (DTL) are used to increase the beam energy. In all cases involving the cavities, the energy of the rf power delivered from the klystron is transferred to the beam and the ions are accelerated. The klystron typically produces 1.0 MW of power at 425 MHz. The low-level rf (LLRF) electronics senses the cavity field and through an active control loop varies the drive to the klystron to maintain this field. The specifications for the field control are ±0.5° in phase and ±0.5% in amplitude.

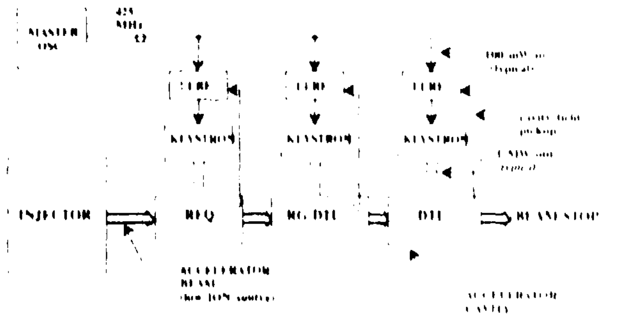

Fig. 1. Basic block diagram of NPB accelerator.

Figure 2 shows a more detailed view of the rf system control loop that drives each cavity. A fixed-frequency oscillator generates the 425-MHz reference rf signal. The LLRF electronics controls this signal, which is sent to the solid-state amplifier (SSA), to the klystron, and into the cavity.

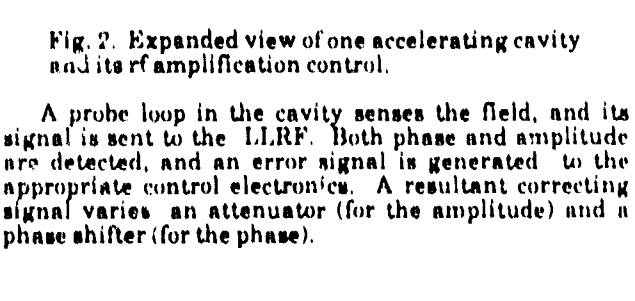

Fig. 2. Expanded view of one accelerating cavity and its rf amplification control.

A probe loop in the cavity senses the field, and its signal is sent to the LLRF. Both phase and amplitude are detected, and an error signal is generated to the appropriate control electronics. A resultant correcting signal varies an attenuator (for the amplitude) and a phase shifter (for the phase).

The functional control loop for the LLRF is shown in Fig. 3. This schematic is generic and applies to both the phase and amplitude control loops. Initially, the computer sends a set-point command. This signal is applied through a proportional, integral, and differential (PID) control that operates on the rf reference signal, which is amplified and drives the cavity. The sensing loop in the cavity sends a signal back to the controller where it is compared to the set point. The resultant error signal is sent to the PID control for correction.

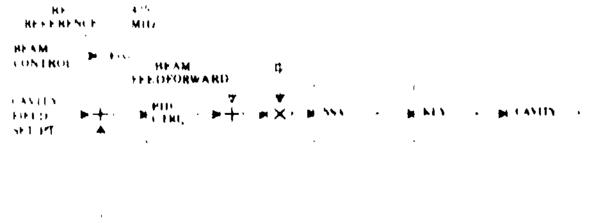

Fig. 3. Functional control loop schematic.

When the accelerator beam enters the cavity, the beam-loading effect will perturb the control loop. To help minimize the transient error caused by this event, a feedforward technique is used and is shown as a summing point just after the PID controller. The beam current and phase are sensed and a function, f(t), conditions these signals.

The above describes the basic loop control; with the help of the feedforward signal, the loop meets the accuracy required to maintain the correct phase and amplitude. However, a DSP technique improves control of the loop. Figure 4 shows schematically where this is applied. The real-time error signal between the set point and the cavity sensing line gives a residual error that the analog to digital convertor (A/D) samples. The DSP stores the error signal and processes the correcting signal. The correction information is sent through a digital to analog convertor (D/A) and is summed back into the loop.

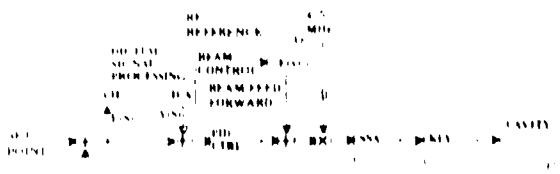

Fig. 4. Functional control loop schematic with DSP.

Applying DSP Technology

Figure 5 shows the relative timing of the control loop. The residual cavity field amplitude and phase errors, e(t), are sampled throughout the pulse, and these time signatures are then averaged with samples from many previous pulses. Thus, under normal operation, the DSP memory contains an approximation to the mean error functions for both amplitude and phase. The stored signals are subsequently processed through a predistortion function to develop the appropriate feedforward signal, y(t).

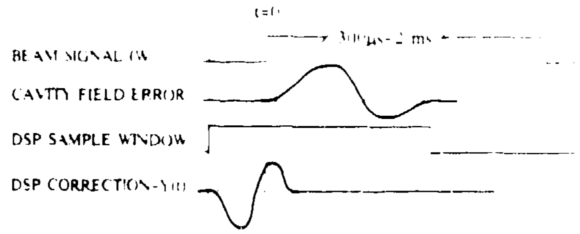

Fig. 5. Timing of control loop.

A block diagram of the cavity field control loops is shown in Fig. 6. Although the adaptive feedforward system is operational throughout the pulse, the most significant loop perturbation is due to transient beam loading. The beam perturbation, W(s) in the Laplace domain, enters the system just before the cavity. Because the correction function y(t) is applied ahead of the beam perturbation, it is time advanced with respect to the beam. This properly compensates for the transport delay through the PID controller, the solid-state amplifier, and the klystron. This operation is straightforward with the use of a DSP.

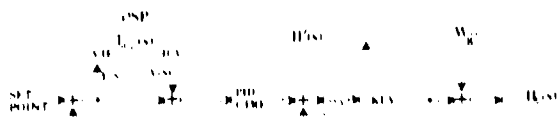

Fig. 6. Representing the control loop by s-plane transfer functions.

In addition to time shifting, the output signal y(t) is processed through a predistortion filter that corrects for the frequency response of the loop to provide optimal cancellation of the disturbance. Two methods of determining the form of the correction signal are discussed here. The first method is an analytical approach using the known transfer functions of the loop. The goal is to provide a y(t) that makes e(t) zero. The analytical approach is analyzed in the s-domain for convenience.

Referring to Fig. 6, the beam disturbing the loop (W_B) gives an error (E_B) as

$$E_B = W_B H_B ,$$

where

$$H_B = H_C/(1 - H_C H') .$$

If the output of the DSP (Y) disturbs the loop, then the resulting error (E_D) would occur:

$$E_D = Y H_D ,$$

where

$$H_D = H_C H'/(1 - H_C H') .$$

To produce a Y that cancels the beam disturbance (W_B), the following equality is met:

$$E_D + E_B = 0 \ ;$$

i.e., the disturbance caused by the beam plus the disturbance caused by the DSP function is zero. Substituting for E_B and E_D,

$$YH_D + E_B = 0$$

or

$$Y = -E_B/H_D \, .$$

The DSP has to realize a transfer function T_{DSP} to counter the beam error $-E_B$ and produce a correction signal Y. Thus,

$$T_{DSP} = Y/E_B = -E_B/E_B H_D = -1/H_D \qquad (1)$$

Equation (1) is a negative inversion of the transfer function of the loop; thus, Y(s) is a leading function, inverted, and a feedforward technique is required to realize this result. The transfer function H'(s) is stable and known, and the DSP determines the s-domain representation of Y(s).

The second method of finding the correction signal uses a heuristic analysis of the loop response to derive a predistortion function. Delays exist in applying the correction signal through the PID controller and klystron because of the poles associated with these components. Thus, for each pole in H'(s), a delay occurs in the correction signal reaching the cavity field.

In the sample time domain, the error signal is E(N,t), where N represents the number of the accelerator pulses. The signal E(1,t) is the first sampled error signal and consists of a number (depending on the sample rate of the A/D) of digitized samples of the error signal. No correction signals, y(t), are sent out on the first accelerator beam pulse because this is the first E(t) sampled.

The algorithm used for determining y(t) is

$$y(N,t) = y(N - 1,t) + A \cdot e(N,t - \tau_1) + B\, e(N,t - \tau_2) \, . \qquad (2)$$

That is, the correction signal y(t) for the present beam pulse N is the previous correction signal y(N − 1,t), plus a set of weighted error signals advanced by τ_1 and τ_2. The weighting constants A and B, and τ_1 and τ_2, were varied until the best results were obtained.

This system was modeled with a commercially available control system modeling program run on an IBM PC/AT. From this model the resultant error in the loop was found. Subsequently an algorithm described by Eq. (2) was added to the model. Figure 7 shows how the loop error was reduced with this algorithm.

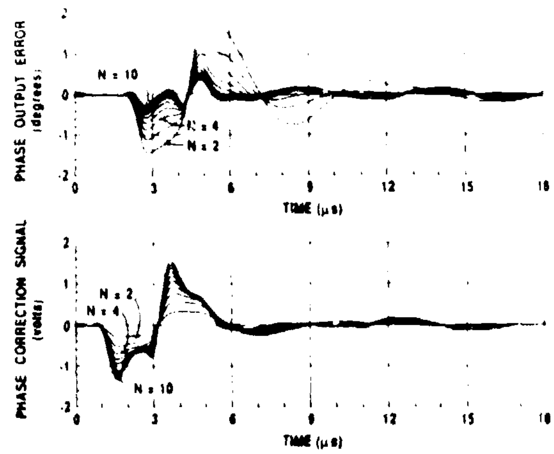

Fig. 7. Reducing the loop error with an iterative approach.

Conclusions

The actual accelerator will have a DSP programmed to implement the algorithm that both Eqs. (1) and (2) describe. The modeling for Eq. (2) is very encouraging, showing that this feedforward control technique will eliminate residual error that augments the fast analog loop and improves the control specifications of the system.

The design of the NPB accelerator will employ one or both of these methods. Further work will simulate Eq. (1) with modeling, and adaptive algorithms will be explored to permit the DSP predistortion function to conform to drifting and aging components.