ADAPTIVE FEEDFORWARD IN THE LANL RF CONTROL SYSTEM*

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Abstract

This paper describes an adaptive feedforward system that corrects repetitive errors in the amplitude and phase of the RF field of a pulsed accelerator. High-frequency disturbances that are beyond the effective bandwidth of the RF-field feedback control system can be eliminated with a feedforward system. Many RF-field disturbances for a pulsed accelerator are repetitive, occurring at the same relative time in every pulse. This design employs digital signal processing hardware to adaptively determine and track the control signals required to eliminate the repetitive errors in the feedback control system. In order to provide the necessary high-frequency response, the adaptive feedforward hardware provides the calculated control signal prior to the repetitive disturbance that it corrects. This system has been demonstrated to reduce the transient disturbances caused by beam pulses. Furthermore, it has been shown to negate high-frequency phase and amplitude oscillations in a high-power klystron amplifier caused by PFN ripple on the high-voltage. The design and results of the adaptive feedforward system are presented.

Introduction

The potential closed-loop bandwidth of most feedback RF-field control systems is limited to a few hundred kHz due to the physical properties of the high-Q accelerator cavities, the high-power RF amplifiers, and the time delays attributed to the large physical distances between equipment. Any disturbances to the RF-field amplitude or phase that have spectral components beyond the closed-loop bandwidth will not be corrected. In fact, the closed-loop system often compounds the disturbances that occur around the loop roll-off frequency due to loop gain-peaking. The optimization of rise-time for a PFN design can lead to high-frequency ripple on the high-voltage supply to the high-power RF amplifier. The PFN ripple translates directly into high-frequency amplitude and phase ripple in the RF field within the accelerating cavity. For pulsed accelerators, the beam turn-on disturbance causes transient errors in the field amplitude and phase for a few microseconds as the feedback loop recovers. These high-frequency RF-field errors cannot be corrected with conventional closed-loop feedback techniques and can result in errors in the output beam energy. Consequently, other means must be used to negate the effects of high-frequency disturbances.

Feedforward techniques are commonly used to predict system disturbances and correct them before the output parameters are affected. Feedforward functions can either be analytically derived in an open-loop manner or experimentally measured and adjusted in a closed-loop manner. The open-loop technique measures an input parameter (such as the disturbance source) and determines a correction function based upon the known system dynamics. The closed-loop method requires that both input and output parameters be observed to determine a cause-and-effect relationship in which the input is adjusted.

For the RF-field control system, the system dynamics relating PFN ripple and transient beam disturbances to the cavity RF field are complex and not well defined. Consequently, a closed-loop feedforward method is used in which the correction function is continuously adjusted or adapted as the system operates. Due to the repetitive nature of the pulsed accelerator, errors in the RF-field parameters can be measured for many RF pulses, creating a collection, or ensemble, of error signals. The LANL closed-loop adaptive feedforward system uses the ensemble of past error signals as inputs to calculate the correction function. As each successive correction function is applied to the system, its waveform is improved through adaptation, eventually reducing the average error close to zero. Because the feedforward function is updated with each successive RF pulse, it will continuously adapt as the accelerator is operated and track any time-varying system dynamics.

Theory Of Operation

A feedforward system creates a correction signal that is applied concurrently with the disturbance that it attempts to correct. In this sense, there are no inherent limitations to the bandwidth of a feedforward system. The LANL system topology shown in Fig. 1 indicates that the feedforward system provides the correction signal at the system input, because a feedforward output signal would require impractical RF levels. Because the correction function is applied at the system input, the dynamics of the system must be accounted for so that the feedforward signal occurs concurrently with the field disturbance.

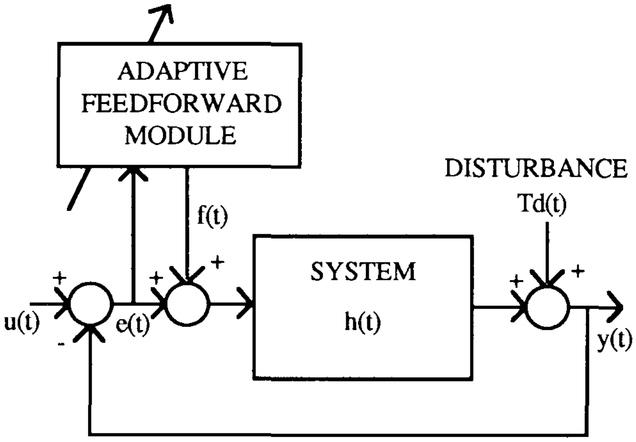

Fig. 1 Topology of LANL feedforward system

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An analysis of the system using Laplace transform methods results in the following equation:

$$Y(s) = \frac{H(s)}{1 + H(s)} U(s) + \frac{H(s)}{1 + H(s)} F(s) - \frac{1}{1 + H(s)} T_d(s) . \quad (1)$$

In order for the disturbance effects to be offset by the feedforward signal, the last two terms in this equation must be equal. Accordingly, the following convolution equation must apply:

$$f(t) = h^{-1}(t) * T_d(t) . \quad (2)$$

Ideally, the characteristics of the feedforward signal should include an inverse of the system transfer function, $h^{-1}(t)$, in order to offset the effects caused by applying the feedforward signal at the system input. Because the system transfer function is time-varying and difficult to predict, adaptive techniques are used instead. The essential property of the correction function required to accurately model the inverse transfer function is the time advance necessary to offset the group delay caused by the limited bandwidth of the system. The correct time advance enables the adaptive convergence upon the exact correction function that will minimize the average error signal. The adaptation process results in a correction function that includes the impulse response for the inverse of the system as part of its waveform. The feedforward correction function is advanced in time when it is applied at the input to offset the group delay of the system. Advancing the correction signal in time creates a non-causal system that is physically unrealizable. Consequently, in order to use this feedforward technique, past error signals must be used to predict the current error signal.

Within a pulsed accelerator, many of the high-frequency disturbances are repeated with the pulsed occurrence of the RF field and the particle beam. An average of the ensemble of the loop error signals has a non-zero waveform. This average is the expected error waveform that depicts the high-frequency repetitive errors that are not corrected by the feedback control system. The purpose of the adaptive feedforward system is to predict a feedforward correction function that will force the expected error signal to zero. The correction function is computed from the current error function along with the accumulated ensemble of past error functions. A mathematical model describes this computation as follows. Each pulse, a new prediction for the feedforward correction function, $f_N(t)$, is computed from the ensemble of past error signals, $e_0(t) \ldots e_{N-1}(t)$. While the index indicates the time within the current pulse, the subscript defines the waveform number within the ensemble of waveforms for many RF pulses. This operation is described by the following equation:

$$\begin{aligned} f_N(t) &= \sum_{i=0}^{N-1} k_i \bullet e_i(t+\Delta T) \\ &= \sum_{i=0}^{N-2} k_i \bullet e_i(t+\Delta T) + k_{N-1} \bullet e_{N-1}(t+\Delta T) \\ &= f_{N-1}(t) + k_{N-1} \bullet e_{N-1}(t+\Delta T) . \qquad (3) \end{aligned}$$

The time advance is depicted in these equations by the ΔT that appears in the time-index of the error signals. Notice that the data for all but the most recent error signal is accumulated into the previous feedforward function. This allows the calculations to be accomplished with a single multiply/accumulate function.

The characteristics of the feedforward function must cause the adaptation algorithm to converge on a stable result that minimizes the average system error [1]. In order for the adaptive feedforward system to operate properly, the individual weights and the time advance must be optimized. The feedforward technique seems to be robust with stable solutions resulting from many combinations of weight and advance parameters. A methodology for optimization needs to be evaluated in more detail.

Implementation

The LANL RF control system operates upon the in-phase and quadrature (I&Q) components of the cavity RF field [2]. Consequently, the LANL feedforward system is implemented to measure and correct the error signals for the cavity field I&Q (See Fig. 2). The dynamic properties of the I&Q variables are equivalent, and thus feedforward prediction and adjustment is simplified because the weighting constants and time advances are identical. An amplitude-and-phase feedforward system would require the simultaneous but separate adjustment of the weights and advances for both amplitude and phase, thus doubling the order of complexity. The LANL feedforward hardware is implemented as two independent channels that can be used as two generic signal processors. This flexibility allows the same device to be used in an I&Q or amplitude-and-phase control system.

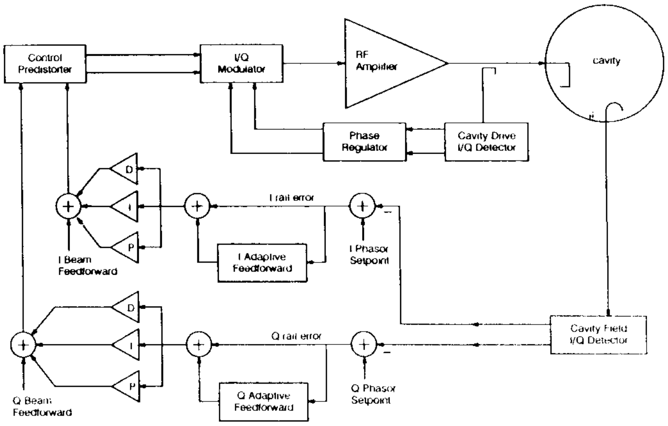

Fig. 2 LANL RF control system

The mechanical medium selected for the adaptive feedforward module is the VXIbus architecture. This is consistent with the rest of the LANL RF control system, which is implemented using the VXIbus packaging format. Consequently, the adaptive feedforward functionality can be added as a modular addition to any LANL RF control system. The VXIbus allows all timing, diagnostic, and data transfer functions to be accomplished over the backplane. The adaptive feedforward instrumentation can make use of the high-performance processing capabilities of the VXIbus. This feature allows complex processing algorithms to be used to adjust the weighting factors and advance parameters to optimize the adaptation performance.

Digital signal processing technology was chosen for the adaptive feedforward design because error and correction waveforms for a large number of pulse must be processed, stored, and used to generate outputs. Consequently, each error signal must be digitized for use in a digital signal processor. Using the error data from a number of previous pulses, a digital processor calculates the desired feedforward signal required to reduce the magnitude of the next error signal. In addition, digital filtering techniques can be used to adjust the spectral properties of the feedforward signal. Both finite impulse response (FIR) and infinite impulse response (IIR) filtering can be performed upon the data structures. IIR filtering is used in the LANL design to reduce memory requirements, because only the accumulation sum needs to be stored in memory. Complex IIR filtering techniques can be used to affect the spectral properties of the correction function by varying the weighting factors as the system operates. If a fixed weighting factor is used for all pulses, the adaptive feedforward function becomes an integral control function, with the adaptation speed adjustable by the fixed weighting factor. There is a tradeoff between adaptation settling time and the stability of the adaptation algorithm. Gains greater than 0.1 create oscillatory conditions where the impulse response of the inverse system cannot be adaptively incorporated into the correction function.

For the LANL adaptive feedforward design, the digital signal processor is based upon the Analog Devices ADSP-1010B multiplier/accumulator integrated circuit. The module contains 512 kbtyes of memory for storage. This system architecture allows a maximum pulse width of 6.5 msec, and a maximum duty cycle of 25%. A sampling rate of 10 Msamples/second and resolution of 12 bits was chosen for the analog-to-digital and digital-to-analog conversion processes. The anti-aliasing and reconstruction filters used in the digital-to-analog and analog-to-digital conversions have cutoff frequencies of 3.5 MHz. This 3.5-MHz bandwidth for the feedforward system represents an increase in bandwidth over the feedback control system by a factor of ten. The current configuration of the LANL RF control system allows errors as small as 25 ppm to be detected by the adaptive feedforward system.

Results

The original design of the adaptive feedforward device was initiated by the system design requirements for the free-electron laser (FEL) project at the University of Twente in The Netherlands. The Twente RF system is based upon a 1300-MHz klystron amplifier that is supplied with high-voltage through a PFN. The PFN design resulted a fast rise-time for the high-voltage pulse, but with a ripple frequency of 500 kHz. This 500-kHz ripple resulted in phase errors in the accelerating RF field greater than 1%. The corresponding fluctuations in the beam output energy were larger than the design goals for the FEL. Consequently, this feedforward system was implemented to negate the affects of the 500-kHz PFN ripple.

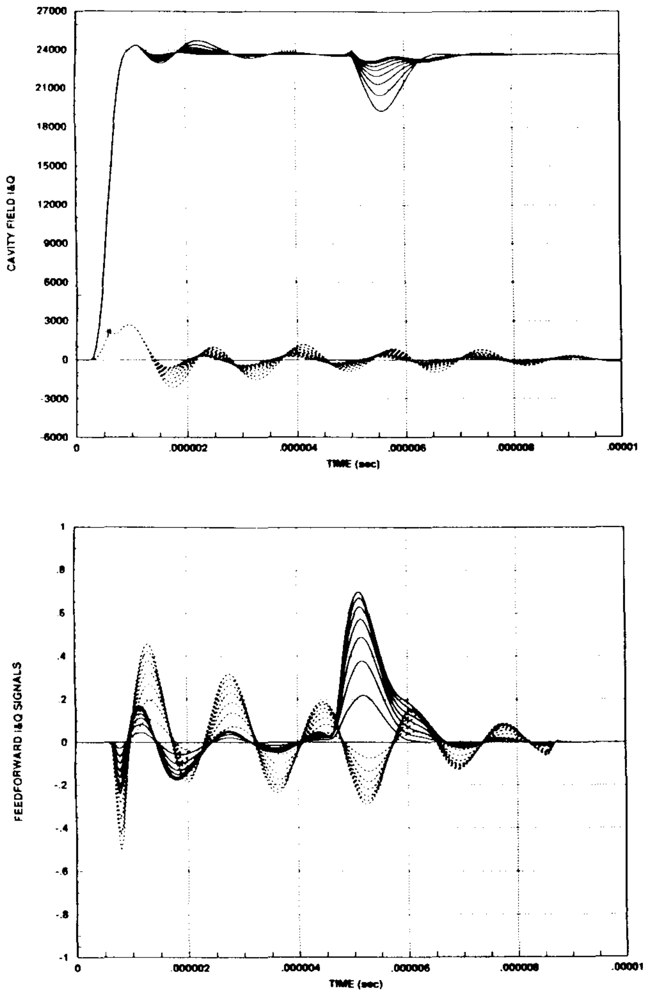

Fig. 3 Feedforward results over a number of cycles

An elaborate modeling effort was pursued as a design mechanism to select and verify the implementation. Fig. 3 shows the modeling results for the design described in this paper. These results show that as the system operation progresses, the correction function improves and the error signal is reduced. In actual tests, the adaptive feedforward module has been shown to reduce the error magnitude caused by a 500-kHz disturbance from 10% to 0.05%. A step transient disturbance has been reduced similarly. The adaptive feedforward techniques have demonstrated a manner to significantly reduce repetitive high frequency disturbances in an RF control system. These techniques are effective even in the absence of detailed information regarding the system dynamics.

References

[1] B. Widrow and S. Stearns, *Adaptive Signal Processing.* Englewood Cliffs, New Jersey: Prentice-Hall, Inc.,1985, pp. 270-361.

[2] C. Ziomek, S. Jachim and E. Natter, "Design of A Multivariable Control System Using Gain-shaping In The Frequency Domain," *Proc. Particle Accelerator Conference.* May, 1991.