SOME NEW METHODS OF RF CONTROL*

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Abstract

This presentation will focus on several recent developments at Los Alamos in the area of RF control for accelerators. Included in the discussion will be in-phase/quadrature (I/Q) field control, the application of six-port reflectometers for cavity instrumentation and resonance control, a technique for phase stabilization of critical RF cables, an application of state-variable feedback for field control, and the direct integration of RF and computer-interface hardware using the VXIbus standard.

Introduction

The advent of accelerators intended for defense applications has driven research and development in many areas of technology. The important field of RF control is one of these areas. In order to reliably meet the unique objectives of these machines, such as remote operation and automatic startup, the need for a thorough, analytically-based system approach to the RF controls was perceived. This paper is an attempt to share some results of the engineering efforts applied at Los Alamos to this end. This is not intended to be an exhaustive study of RF control methods in the accelerator community at large, and thus unfortunately excludes much important work outside of its focus.

The first sections of this paper will describe two distinct approaches to feedback control of cavity fields, namely I/Q control and state-variable feedback. Then a new approach to cavity resonance control and instrumentation, using a six-port reflectometer, will be outlined. A technique for precise phase stabilization of transmission lines will follow. Finally, the direct integration of the RF controls with the associated computer control hardware, using the VXIbus standard, will be discussed.

I/Q Feedback Control

A new method for feedback control of RF cavity fields is under investigation. Rather than operating on the amplitude and phase (A/P) of the cavity field, this approach controls the in-phase and quadrature (I/Q) components of the cavity field. This technique, as illustrated in figure 1, measures and regulates the I and Q components of the field with respect to an RF reference signal, thereby regulating the field parameters. Some related work can be found in [1-3].

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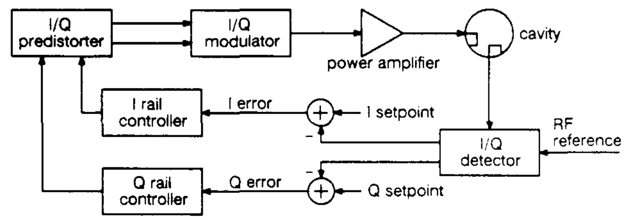

Figure 1. Block diagram of I/Q field control system.

Several important considerations drove the need for I/Q control. The signal processing components required for a typical A/P control system, such as phase shifters and modulators, are usually expensive, bulky and have difficulty achieving the requisite performance. On the other hand, the corresponding processes in an I/Q system can be realized with standard integrated circuits. The precision phase shifter usually required to set the cavity phase in an A/P control system can be eliminated in an I/Q system, as any desired field vector can be selected with the I and Q control setpoints. These tradeoffs are made all the more significant by the requirement for computer-controlled remote operation of the system. The technology used to implement an I/Q system is inherently better adapted to this need. I/Q control also offers a clear path to large-scale integration, with the concomitant benefits in cost and weight.

The response function of an accelerating cavity [4,5] is best described in rectangular (i.e., I/Q) coordinates [6]. The subsequent analysis is also simplified by taking advantage of the isomorphism (i.e., analog) between the real-signal and complex envelope domains [7]. A real-valued bandpass signal, $s(t)$, can be expressed as a linear combination of two orthogonal carriers at the center frequency (ω_d) of the bandpass signal, each amplitude-modulated by a real-valued baseband envelope, as shown in (1).

$$s(t) = m_i(t)\cos(\omega_d\, t) - m_q(t)\sin(\omega_d\, t) \qquad (1)$$
$$m_i(t) = \text{in-phase envelope}$$
$$m_q(t) = \text{quadrature envelope}$$

The complex envelope, $\tilde{s}(t)$, of the bandpass signal is thus described in the time domain as

$$\tilde{s}(t) = m_i(t) + jm_q(t) \qquad (2)$$

The complex envelope retains all of the features of the temporal modulation of the original bandpass signal, but with the center-frequency variation suppressed. This transformation permits the RF system to be accurately modelled at baseband, obviating the need to use a sampling rate based on the RF frequency. It also gives direct insight into the behavior of the RF system and forms the analytical basis for the I/Q control system.

The equivalent baseband voltage response ($[\tilde{V}(s)]$) of a bandpass circuit to an arbitrary current distribution ($[\tilde{I}(s)]$) is determined from

$$[\tilde{V}(s)] = \begin{bmatrix} V_i(s) \\ V_q(s) \end{bmatrix} = \begin{bmatrix} Z_c(s) & Z_s(s) \\ -Z_s(s) & Z_c(s) \end{bmatrix} \begin{bmatrix} I_i(s) \\ I_q(s) \end{bmatrix} = [\tilde{Z}(s)][\tilde{I}(s)] \quad (3)$$

The components of $[\tilde{Z}(s)]$ for a parallel-resonant circuit detuned from the drive frequency are[1]

$$Z_c(s) = \left(\frac{R_c}{\tau}\right)\left(\frac{s + a_{1c}}{s^2 + b_1 s + b_2}\right)$$
$$Z_s(s) = \left(\frac{R_c}{2Q\tau}\right)\left(\frac{s + a_{1s}}{s^2 + b_1 s + b_2}\right) \quad (4)$$
$$a_{1c} = \left(\frac{1}{\tau} - \frac{\Delta\omega}{2Q}\right) \qquad b_1 = \left(\frac{2}{\tau}\right)$$
$$a_{1s} = \left(\frac{1}{\tau} + 2Q\Delta\omega\right) \qquad b_2 = \left(\frac{1}{\tau^2} + \Delta\omega^2\right)$$

τ = cavity damping time constant (sec)
R_c = cavity shunt resistance (ohms)
Q = cavity unloaded quality factor
$\Delta\omega = \omega_0 - \omega_d$ = cavity detuning frequency (rad/sec)
ω_d = cavity drive frequency (rad/sec)
ω_0 = cavity resonant frequency (rad/sec).

Taking into account the boundary conditions at the drive port junction and beam loading [8,9], the equivalent baseband operational scattering model for a cavity detuned from the drive frequency is as shown in figure 2.

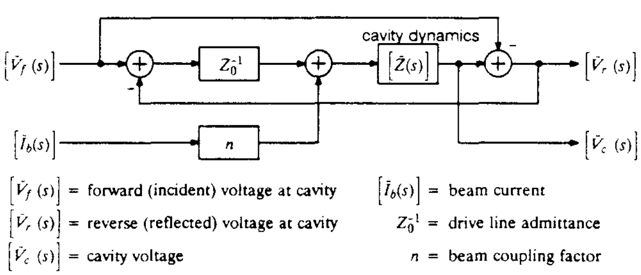

Figure 2. Operational scattering model of a cavity.

The transfer function of figure 2, $[\tilde{H}(s)]$, from forward voltage to cavity voltage is

$$[\tilde{H}(s)] = 2(Z_0^{-1})\left[I + Z_0^{-1}[\tilde{Z}(s)]\right]^{-1}[\tilde{Z}(s)] \quad (5)$$

This transfer function has the same structure and order as does $[\tilde{Z}(s)]$, but with the pole and zero locations shifted as functions of Z_0. With I/Q control, the dynamic crosscoupling of the cavity can be completely removed with rudimentary linear circuits at baseband. Decoupling can also be achieved with A/P control, albeit with greater difficulty [10]. This function is incorporated as the I/Q predistorter in figure 1. In essence, the predistorter deliberately crosscouples the drive signals to the cavity and the cavity then "unscrambles" them, with the overall effect of orthogonal control; thus the term predistorter. When the proper predistortion function $[\tilde{P}(s)]$ is concatenated with $[\tilde{H}(s)]$ as shown in (6), the result is a compound response $[\tilde{F}(s)]$ which is decoupled. The required I/Q predistortion functions are simple, linear and realizable.

1. The equations given in [6,8] differ inadvertently from those shown here by a factor of two. The functions shown here are indeed correct.

$$\begin{bmatrix} H_c(s) & H_s(s) \\ -H_s(s) & H_c(s) \end{bmatrix} \begin{bmatrix} P_c(s) & P_s(s) \\ -P_s(s) & P_c(s) \end{bmatrix} = \begin{bmatrix} F_c(s) & 0 \\ 0 & F_c(s) \end{bmatrix} \; ; \quad (6)$$

$$P_c(s) = 1 \text{ , and } P_s(s) = -\left(\frac{H_s(s)}{H_c(s)}\right)$$

A significant difference between the I/Q and A/P control methods lies in their relative tolerance of time-varying phase shift (i.e., droop) in the power amplifier. In an A/P control loop, phase droop represents a phase rate perturbation. Integral feedback gain in an A/P loop will reduce this to a constant phase tracking error of the cavity field. The same droop in an I/Q system induces a rotation of the control vector, the effect of which, for small phase shift variations, is to slightly crosscouple the I and Q loops. If not held within limits, this phase shift can lead to destabilization of the loops. This can be avoided by direct feedforward compensation of or local feedback around the amplifier, and thus is usually not a serious practical problem.

State-Variable Feedback

An intriguing approach to RF control using state-variable feedback is under investigation by J. Johnson [11]. Readers are referred to the cited reference for more detailed information; only a brief overview will be given here. A block diagram of this scheme is shown in figure 3. In this implementation, samples of three system states are scaled in magnitude (a_i) and phase ($\Delta\phi_i$) and applied as feedback functions. The sum of these weighted feedback functions is compared to an RF reference signal, and their difference is used to drive the RF system.

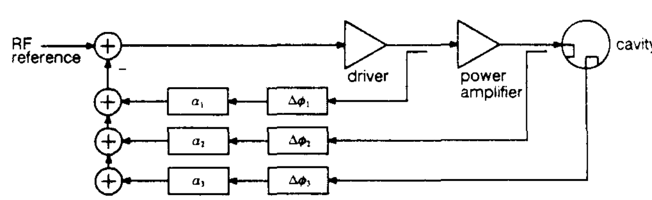

Figure 3. Block diagram of state-variable control system.

Two significant benefits accrue from this approach. A state-variable feedback system [12,13] which utilizes direct, proportional observations of system states can be shown to have a high degree of stability and performance robustness with respect to variations of the plant. Thus gain and bandwidth variations in the power amplifier, for instance, do not have a strong effect on the behavior of the closed-loop system. Also, as seen in figure 3, all feedback and signal processing functions are performed directly at the RF frequency. The elimination of conversion, detection, and modulation equipment can have a substantial impact on the system cost. Related analysis of RF feedback can be found in [14,15].

However, restricting the feedback functions to proportional gain limits the ability of the feedback loop to suppress external disturbances, such as beam loading. The lack of Nyquist–type gain shaping of the feedback functions, particularly integral gain, does not allow the available loop gain to be customized for disturbance suppression. Similar to the I/Q approach, the state variable control system also exhibits sensitivity to such things as power amplifier phase droop, in that large phase shift variations can destabilize the loop. Within these constraints the state–variable control system works well and has been demonstrated on a FEL cavity.

Resonance Control

This section describes a system with which to measure and tune the properties of resonant accelerating structures at high power levels. With the addition of a few passive components, a standard dual directional coupler can be transformed into a six-port reflectometer [16,17], as shown in figure 4. This device can be used to determine the vector reflection coefficient of a cavity attached to the coupler simply by measuring the RF power at each of the four sidearm ports.

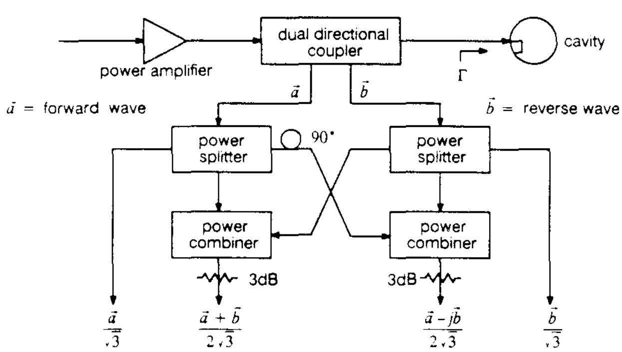

Figure 4. Block diagram of a six-port coupler.

There is no need for vector ratio processing, and any phase shift induced in the sidearm signals, say by cables, is irrelevant. The vector nature of the measurement is inferred from the correlations among the sidearm signal levels, as shown in (7) [18]. For noncritical applications, the calibration constants can be determined by inspection of the network in figure 4. For applications requiring greater precision, a calibration procedure can be used to implement vector error correction in software. Many useful calibration procedures are in existence, but an approach tailored to high-power applications has been developed [19]. Experimentally, reflection measurements made with a calibrated six-port reflectometer, operating at 1kW, matched those made with a calibrated automatic network analyzer to less than 1%.

$$\Gamma = \frac{\sum_{i=1}^{4}(F_i + jG_i)P_i}{\sum_{i=1}^{4} H_i P_i} \qquad (7)$$

Γ = reflection coefficient of cavity
F_i, G_i, H_i = real calibration constants of six-port coupler
P_i = power measured at i^{th} sidearm port

By sampling and digitizing the measured data from a six-port reflectometer, resonance control of a cavity in a pulsed RF system has been demonstrated. This was achieved in software by applying a feedback control algorithm, via a slug tuner, to minimize the susceptance observed at the plane of the detuned short [20]. Figure 5 illustrates a typical computer display of this tuning process, wherein a cavity which is initially detuned is brought into resonance along a constant–conductance contour of the Smith chart.

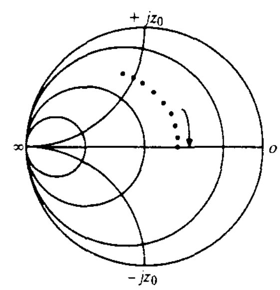

Figure 5. Reflection coefficient locus displayed during resonance control.

This device can also be used to instrument an accelerator RF system. By making susceptance slope measurements [21] at appropriate times during the RF pulse, the unloaded Q, beam–loaded Q and beam loading factor can be determined. These measurements can be made without disturbing the normal operation of the accelerator. Good agreement has been found between high–power and low–power Q measurements on a cryogenic DTL [22].

RF Transport Stabilization

A common requirement in accelerators is a phase-stable means of delivering RF signals to their appropriate points of use. A successful solution to this problem [23] is shown in figure 6, wherein a signal from a reference oscillator is transported to a remote load. The circuit shown operates as follows. An RF calibration signal at a frequency equal to one and one–half times the frequency of the signal to be delivered to the load is split and applied both to a phase detector and another splitter/combiner where it is then transmitted through a diplexer onto a single coaxial line. Upon arrival at a second diplexer, this calibration signal is reflected, via a short-circuit termination, back toward the first diplexer where it is extracted from the coaxial line and applied to the phase detector. The output of the phase detector is filtered and proportional and integral control actions are developed from this information. The output of the feedback controller is used to drive the phase shifter via the DC motor in such a way as to hold the electrical length of the transport path constant. The RF reference signal is superimposed and transmitted on this same stabilized path. A similar technique for optical signals is described in [24].

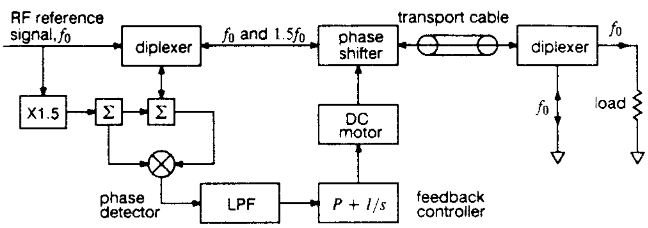

Figure 6. Phase-stable RF transport block diagram.

A diplexer is a device which is used to combine or separate two signals of different frequency. Space does not allow a full description of the diplexer that was used, but suffice it to say that it exhibited the required high degree of phase stability. The results of a 68 hour test of this system are shown in figure 7. A 150 foot coax was used for the transport cable. The output phase was held constant to within ± 0.036° at 435MHz.

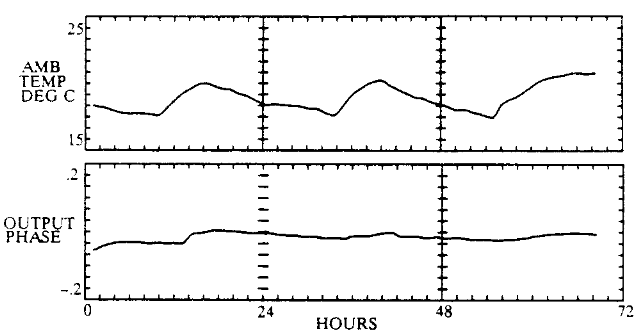

Figure 7. Phase-stable RF transport test results.

System Integration

A new approach to the implementation and integration of RF controls has been undertaken. The I/Q field control, six-port resonance control, and the phase-stable transport systems are being realized in card-modular form using the VXI standard [25]. This emerging standard was developed by a consortium of major instrument manufacturers, and extends the ubiquitous VME standard to support precision instrumentation and RF applications. A typical layout for a VXI module that is used for RF control is shown in figure 8.

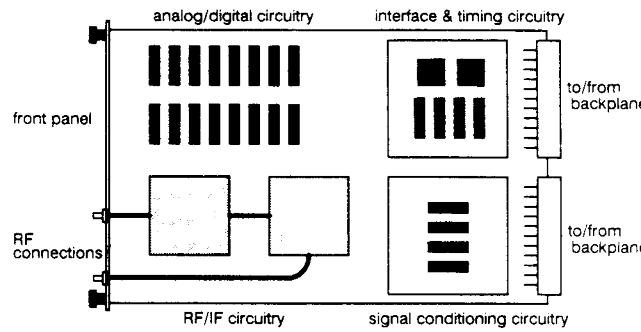

Figure 8. Typical layout of a VXI module for RF control.

The integration, setup and operation of the RF control system is greatly simplified by this modular approach. The functions of timing, analog I/O, and digital I/O are directly accessed over the VXI backplane to/from each individual module, thus vastly reducing cabling and interconnects. The system clock and master trigger are broadcast across the VXI backplane, and timing pulses are then generated on each card by addressable countdown registers. The interface is a straightforward VME-style register-based design with minimal software requirements. Because all of the RF signal processing is done electronically, troublesome RF components, such as trombone lines, have been eliminated. The benefits to system reliability and maintainability are clear.

By design, the RF control system is fully operable from a remote location. All control parameters, for instance integral feedback gain, drive phase adjustment, and fast-protect thresholds, are remotely programmable. This approach also enables the RF control system to be easily adapted to a wide variety of accelerators simply by loading the appropriate control parameters. What has been achieved to a large extent is a generic, modular RF control system.

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