FEEDFORWARD CONTROL OF ACCELERATOR RF FIELDS*

by

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Summary

A new and very effective technique for accelerator field control is demonstrated, using a feedforward control loop to complement a standard feedback controller. The accelerated beam current envelope, which acts as a load disturbance on the accelerator field amplitude and phase, is detected upstream from the module to be controlled. Due to differences in propagation velocity in the accelerator and external cables, true anticipating control is possible by feeding the current signal forward to the controller. In tests with full beam loading (22%) in the first 201.25 MHz tank at LAMPF, peak amplitude error was reduced to 0.4% and settling time to 20 μsec at beam turn-on.

Introduction

Conventional methods[1-4] presently used to control the phase and amplitude of accelerator fields employ the feedback principle and are characterized by rather poor control during transient periods of heavy beam loading. If the load changes do not occur too often during the pulse, and the pulse is long enough, such controllers eventually do reach a steady-state and can return the field very closely to the desired values.

There are several reasons why these controllers are limited; some are built into the typical accelerator system. First, requirements for shielding cause the system to be physically large, resulting in time delays in signal transmission. Slow group velocities in some accelerator structures and some high power components also contribute to the pure time delay in the control loop. Second, the high price of rf power does not allow procurement of a large margin to be used as an overdrive reserve in the control problem, and components which saturate only slightly above their design output are a fact of life.

The third reason is more fundamental -- a feedback controller cannot begin to operate until an error has already been generated. With time delays and limited reserves, the error is bound to be large and of long duration.

If information about a load disturbance were transmitted to the controller in such a way that a correction of the same shape as the load disturbance were applied at the same instant the controlled variable began to feel the disturbance, there could theoretically be no error at all. This is what the feedforward controller attempts to do. In practice, it is not uncommon to realize a factor of ten or more improvement in peak error and settling time.

In the case of an accelerator, the load disturbance is beam loading, and the beam current envelope is an easily measured signal directly proportional to the effects of the beam on the cavity field. The problem is to get a power correction to the cavity at the same time the beam load arrives. In heavy particle accelerators where the average particle velocity is low, anticipation can be achieved quite easily by sensing the beam current upstream from the cavity to be controlled, and transmitting the signal to the controller through high-propagation velocity cable. It is difficult to achieve this natural anticipation in high beta machines, but measurements can be used to generate simulated feedforward signals.

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Derivation of Feedforward Controller[5]

Referring to Fig. 1, the output characteristics, c, of a process are influenced, in general, by manipulated inputs, m, and load disturbances, q. The K's and g's are the steady-state and dynamic gain terms, respectively, affecting the variables. All of these quantities may be matrices, but are treated here as single variables for clarity.

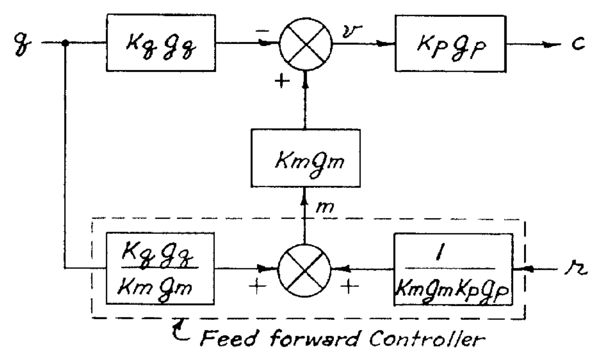

Fig. 1

$$c = (mK_m g_m - qK_q g_q)K_p g_p \quad . \qquad (1)$$

The controlled variable c is supposed to equal the reference, r, so substituting r for c and solving for m gives the feedforward control law directly, with both static and dynamic compensation:

$$m = \frac{r}{K_p g_p K_m g_m} + \frac{qK_q g_q}{K_m g_m} \qquad (2)$$

If all the compensation were physically realizable, the system in Fig. 1 would both track r and cancel q perfectly. Even with practical constraints, very good results are possible, as shown below.

Addition of Feedback

The feedforward control law is seen to depend on a very accurate measurement of the load disturbance and exact compensation for the network gains. In applications with very tight control tolerances, such as accelerator field control, the required accuracy cannot usually be realized in the forward loop. If the controlled variables are measurable, as they are in the accelerator, then feedback can also be applied to provide the final trim to the system; see Fig. 2.

The way in which the two controllers complement each other is very important. There are absolutely no stability problems associated with the feedforward controller. Further, it is very "intelligent," since it knows how to handle a disturbance directly, but it may lack high accuracy in the realization of the control law due to technique or economic reasons. On the other hand, the feedback controller is geared to solve a problem by trial and error, and can do so very accurately. It can cause instability, but when combined with the feedforward controller, the gains in the feedback controller can usually be lowered considerably.

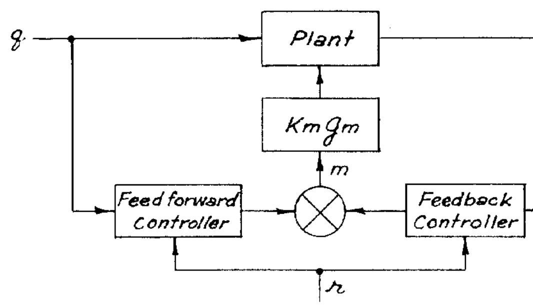

Fig. 2

Accelerator Field Control

The following example is taken directly from preliminary experiments performed on Module 1 of the LAMPF 201.25 MHz post-coupled linac during 5 MeV beam tests. As a result of these tests, certain deficiencies, explained below, were found; the correction of these promises even better results in the future. However, this early example clearly shows the technique and is perhaps even more impressive in that very dramatic improvement was made even with fairly unresponsive hardware.

The critical components in a typical field control loop may each be characterized by a time delay and a single lag for most purposes. The slowest item is the tank, which had a (loaded) time constant of about 50 μsec in this case. A time delay of about 0.8 μsec was incurred from the rf amplifier output to the response seen at the controller from a probe located ¼ of the tank length from the downstream end. (Shortening this time delay by relocating the pickup probe nearer the center of the tank is planned.)

The second restrictive element is the amplitude modulator and rf amplifier, which in this case had a time constant of 1.6 μsec and a time delay of 1.5 μsec. The available power output was only very slightly greater than the required power with full intensity beam of 16 mA peak. (The large time delay resulted from measures taken to suppress parasitics. Work now in progress is expected to reduce the delay to less than 1 μsec and also to improve the power margin.) The remaining components in both the phase and amplitude control loops are very fast and can be characterized by pure gain terms.

The beam current signal is detected by a current transformer located at the end of the Cockcroft-Walton column at the beginning of the transport system. The tank control probe is about 50 ft downstream; the delay between the times that the controller sees a signal from the current transformer and its effect at the tank is 1.2 μsec. In the example below, the current signal is injected directly into the controller with a simple gain control K_q/K_m only, with no attempt to add the dynamic compensation g_q/g_m.

Consider the action of the feedforward amplitude control loop alone. Since the modulator time constant is much smaller than that of the tank, it can be neglected, leaving both g_m and g_q as pure time delays. A quick analysis of this simple system shows the essentials of the transient response. From Fig. 1:

$$v = (mK_m g_m - qK_q g_q) \quad (3)$$

$$v(t) = [K_m\, m(t - \tau_m) - K_q\, q(t - \tau_q)] \quad (4)$$

where $\tau_m = 2.3$ μsec and $\tau_q = 1.2$ μsec.

Differentiating

$$dv = [K_m\, dm(t - \tau_m) - K_q\, dq(t - \tau_q)] \ . \quad (5)$$

In steady state, the feedforward control law is

$$m = \frac{r}{K_m} + \frac{qK_q}{K_m} \ . \quad (6)$$

Differentiating (6) and substituting in (5) yields

$$dv = [K_q\, dq(t - \tau_m) - K_q\, dq(t - \tau_q) + dr(t - \tau_m)$$

$$= K_q\, dq(\tau_q - \tau_m) + dr(t - t_m) \ . \quad (7)$$

The responses are shown in Fig. 3.

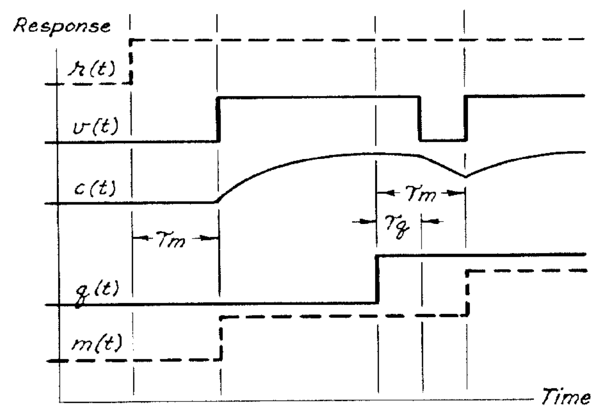

Fig. 3

An error is present for 1.1 μsec after a change in q affects v; however, the delay τ_q has been used to anticipate the required control.

The design of the feedback controller is independent of the feedforward controller for the most part, although certain refinements are desirable in systems which are required to have good response for both reference changes and load disturbances. The addition of feedforward does not ease the design problems for the feedback loop -- it does reduce the excursions required in the feedback path and usually allows the stability margins to be greater.

Figure 4 shows the result achieved in control of cavity field amplitude. The phase and amplitude feedback controllers, both operating, are linear loops with integral and proportional terms. The amplitude loop is augmented by an inner loop around the modulator and rf-amplifier with an incident power signal fed back. The addition of this state-variable has an important part in stabilizing the feedback loop. The response of the feedback controller alone is shown in the "A" traces, with a peak error of 1.2% after the introduction of the 22% beam load, and a settling time of about 40 μsec.

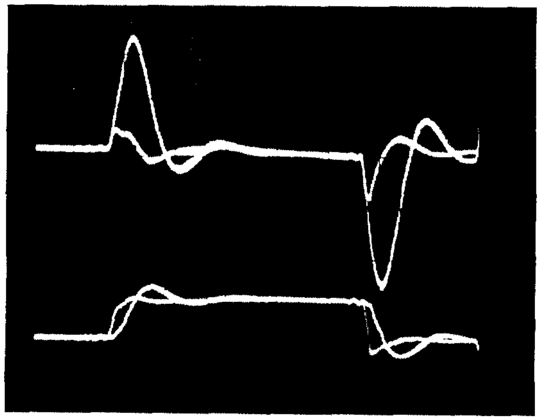

Fig. 4. Top Trace: (-) cavity field during full intensity beam pulse, 0.5%/cm.
Bottom Trace - forward power from rf amplifier, showing 22% beam loading correction.
"A" traces are with feedback control only; both amplitude and phase loops are locked.
"B" traces are with feedforward control added to the amplitude loop.

The simple addition of the feedforward signal to the amplitude loop produces the "B" responses. The peak error at beam time turn-on is reduced to 0.4% and the settling time is about 20 μsec. The area of the transient pulse is also drastically reduced. This improvement is achieved in spite of the fact that the 1.2 μsec of anticipation is only about half of the optimum 2.3 μsec. The same feedforward signal will also be applied directly to the phase control system.

In the early stages of the accelerator where the beam is in the formative stages, an upstream sensor may not stay exactly in the same proportion as the load apparent at the module being controlled. However, as explained above, the feedforward control is not required to have high accuracy if it is augmented by feedback. The sensors for the first 201.25 MHz modules of LAMPF will be the most critical in this respect, since they must precede the transport system and bunchers in order to get enough anticipation. The ratio of Cockcroft-Walton current to current accelerated through Module 1 does stay relatively constant, though, as shown in Fig. 5.

Control of later modules of LAMPF can use current sensors further downstream. In fact, over-anticipation can be achieved, allowing the addition of adjustable time delays for optimum adjustment.

Simulated Feedforward

When the necessary anticipation to overcome a long time delay cannot be obtained in a direct manner, effective control of a pulsed machine can be achieved by using information that is one pulse old, if the pulse-to-pulse repeatability is reasonable. It is important to know about how big the load disturbance is going to be, and when it will occur. By sampling the beam current during the previous pulse and using the information to control the height of a correction pulse which can be positioned at the right time, very good compensation can be achieved. The simple circuits in Fig. 6 have been used at LAMPF.

Conclusion

A simplified derivation of the very powerful feed-

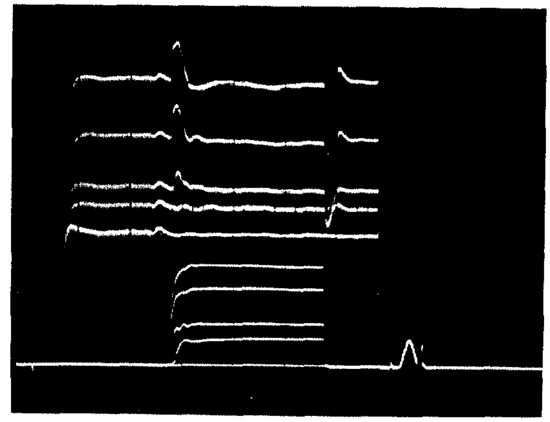

Fig. 5. Top Traces: (-) cavity field, 0.5%/cm with zero offset changed for each trace. Control of beam loading is shown as beam current is varied.
Bottom Traces: beam current at sensor used for feedforward control. 10 mA/cm.
Time Scale: 50 μsec/cm.

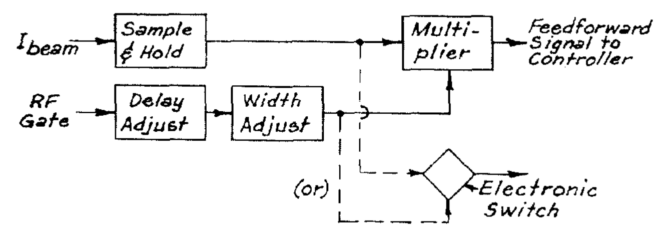

Fig. 6. Simulated beam current feedforward signals.

forward control technique has been presented, and results shown for a typical accelerator application. Dramatic improvement over conventional control is achieved by the addition, in this case, of extremely simple circuitry.

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