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ROBUST RF CONTROL OF ACCELERATORS

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Abstract

The problem of controlling the variations in the rf power system can be effectively cast as an application of modern control theory. Two components of this theory are obtaining a model and a feedback structure. The model inaccuracies influence the choice of a particular controller structure. One can design either a variable, adaptive controller or a fixed, robust controller to achieve the desired objective. The adaptive control scheme usually results in very complex hardware; and, therefore, shall not be pursued. In contrast, the robust control method leads to simpler hardware. However, robust control requires a more accurate mathematical model of the physical process than is required by adaptive control. Our research at the Los Alamos National Laboratory (LANL) and the University of New Mexico (UNM) has led to the development and implementation of a new rf power feedback system. In this paper, we report on our research progress. In section one, the robust control problem for the rf power system and the philosophy adopted for the beginning phase of our research is presented. In section two, the results of our proof-of-principle experiments are presented. In section three, we describe the actual controller configuration that is used in LANL FEL physics experiments. The novelty of our approach is that the control hardware is implemented directly in rf without demodulating, compensating, and then remodulating.

Philosophy of Robustness

In order to synthesize a control architecture for rf systems, a mathematical model must be developed. This requires measuring the gain- bandwidth characteristics of the rf amplifiers and the accelerators. Accompanying each of these measurements is a degree of uncertainty. The causes of these errors are the nonlinearities in the device under test and the lack of precision in the measurement. However, calibrating the diagnostic equipment and then carefully characterizing all the individual subsystems in the amplifier chain can be a time consuming and nonrewarding task. Indeed, you could spend more time explaining errors between different measurements rather then designing a feedback system with the imperfect knowledge you already possess.

An additional uncertainty exists for control designers of particle accelerators - the beam. If you view the accelerator as a resonant structure with a definable 'Q', and view the beam as an impedance, from beam-loading to no beam-loading (or from beam-loading variations), there will be a perturbation in the 'Q'. Therefore, during operation the "poles" of the accelerator move around in the complex plane. The traditional theory of control deals with precise mathematical models and maintains that with good gain and phase margins the physical system will also be stable. Unfortunately, the result of these uncertainties is that although the mathematical feedback system has good phase and gain margins, the physical control system could be unstable. In fact, it is well known that having good gain and phase margins is insufficient to prove physical stability.[1]

During the past decade, the theory of robust control has emerged to deal with the incongruence between the mathematical and physical feedback stability problem. This new theory is an extension to the foundations laid by Bode and Nyquist. That is, by definition, the task of robust control is to analyze and design a stable, high performance control system despite having models with significant uncertainties[1]. It is possible to determine a priori the maximum uncertainty bound beyond which no controller can be synthesized to stabilize the given system.

Robust control is subdivided into two concepts; robust stability and robust performance. Optimal state-feedback is one tool by which to achieve robust stability, there are also output-feedback stability robustness methods[1,2]. No complete synthesize technique currently exists for the robust performance problem and is an open research topic. We decided to pursue the state-feedback concept because of its theoretical results of infinite forward gain margin, -6db reverse gain margin, 60° phase margin, and nonlinear stability margin.

State Feedback

Experimental selection of a state follows from its basic definition: the state of a dynamic system is the smallest set of physical variables such that the knowledge of these variables, together with the input, determine the system's behavior. Since we wish to control the electric fields in the accelerator, which are produced by the rf power flowing into the accelerator, the minimal set is formed by the output of each of the amplifiers and the accelerator. Including internal amplifier physical variables would be more than sufficient, and hence would form a nonminimal set. These outputs or states then determine the behavior of the system.

The methods investigated were a pole placement design and an optimal state-feedback design with its stability robustness properties. In addition, all dynamic control devices were discarded, leaving only the amplifier chain (Fig. 1). Both the amplifiers and the accelerator were modeled as first-order low-pass equivalent filters.

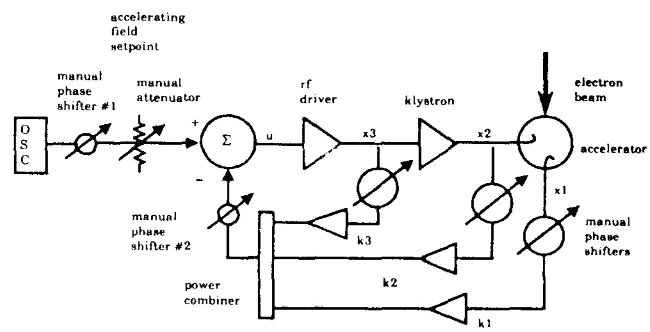

Fig. 1 State Feedback Controller.

The uncertainty enters the model when measuring the -3db bandwidth points and trying to fit this data to a first-order filter. This was done in order to research the simplest model achievable that would still retain feedback system accuracy. The low-pass equivalency retains generality because the control system bandwidth arises from the demodulated version of each signal. The rf driver and the accelerator have normal, smooth frequency transfer functions. However, the klystron does not. Its gain-frequency curve is asymmetric. Below the center frequency, the gain rolloff rate is less than it is above the center frequency. For frequencies close to the center (1.3 GHz ± 4 MHz) the gain curve is flat. The resultant nominal model without beam-loading disturbance is given by

$$dx/dt = \begin{bmatrix} -1.1 & 1 & 0 \\ 0 & -40.25 & 1 \\ 0 & 0 & -7.7 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 5.7 \, x \, 10^5 \end{bmatrix} u \, ,$$

$$y = [1 \quad 0 \quad 0] \, x \, ,$$

with uncertainty entering the A matrix and b vector as

$$\delta A = \begin{bmatrix} \pm.14 & 1 & 0 \\ 0 & \pm 1.5 & 1 \\ 0 & 0 & \pm 2.1 \end{bmatrix} , \; \delta b = \begin{bmatrix} 0 \\ 0 \\ \pm 1.7 \, x \, 10^5 \end{bmatrix} .$$

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Beam loading is a disturbance which induces plant parameter variations in the nominal model.

With simple eigenvalue assignment to [−6.28, −40.2, −7.7] the feedback gains were −77 db, −97 db, and −116 db for k_1, k_2, and k_3 respectively. These gains include the coupling coefficients from the accelerator and the directional couplers. Pole placement does not try to optimize the feedback system. Therefore, eigenmode assignment resulted in some states with no feedback. The residual accelerator field fluctuations were less than 0.03%, but droop across the pulse was significant. Figures 2 through 5 depict open-loopversus closed-loop with beam-loading disturbance

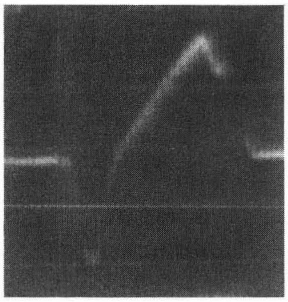

Fig. 2. Open-loop phase variation with beamloading. 2° and 20 μsec per division.

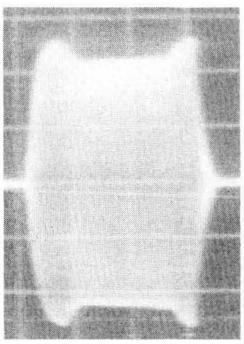

Fig. 3. Open-loop amplitude variation with beamloading. 100 mV and 20 μsec per division.

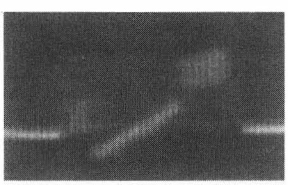

Fig. 4. Closed-loop phase variation with beamloading. 2° and 20 μsec per division.

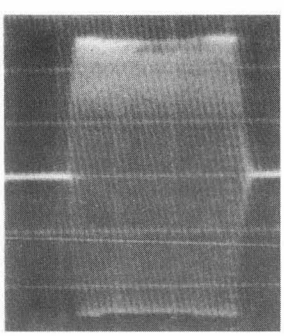

Fig. 5. Closed-loop amplitude variation with beamloading. 100 mV and 20 μsec per division.

Next a Linear Quadratic Regulator (LQR) optimal control approach was used with the following performance index:

$$J = \frac{1}{2} \int_0^{\infty} \left(x^T Q x + u^T r u \right) dt .$$

In the above equation, Q minimizes deviations in the states and r minimizes the control input energy. That is, a small r implies a large power reserve and a large entry in Q implies small deviations in that state.

The optimal control feedback gains were −73 db, −69db, and −40 db for k1, k2, and k3, respectively. Figures 6 and 7 show these results without beamloading. The phase margin was measured to be 75°. The infinite gain margin of an ideal LQR design is destroyed by the fact that every loop has some finite time delay associated with it. One disadvantage with optimal control is that different Q's and r's will result in different feedback gains. The designer must still apply his knowledge of the system in order to determine if the gains make sense. Once you determine the boundary of sensible gains; however, the algorithm will automatically determine what gains are "best" for a given constraint.

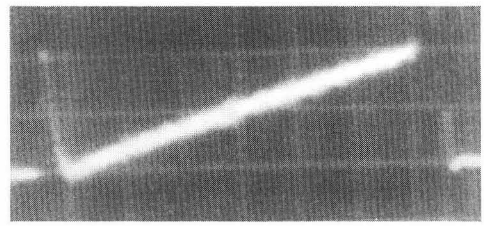

Fig. 6. Closed-loop (phase) optimal control without beamloading. 1° and 10 μsec per division.

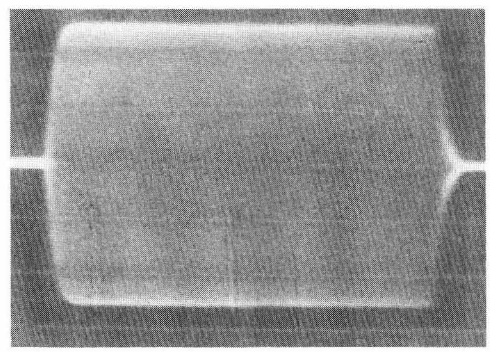

Fig. 7. Closed-loop (amplitude) optimal control without beamloading. 100 mV and 10 μsec per division.

In fig. 1 the three phase shifters in the feedback loops are used to negate the various line lengths at 1.3 GHz. The gains are actually fixed microwave attenuators. The manual phase shifter #2 is used in order to ensure negative feedback. The summer is a passive, 180°, hybrid combiner. The manual phase shifter #1 and variable attenuator are used to experimentally set the correct reference input.

Frequency-shaped State-feedback

The normal state-feedback cannot frequency shape the control system. As seen in the above results, the "proportional-derivitive" control did not produce a high enough gain controller to correct for low frequency disturbances. However, this negative result was not without its merits. There was a significant reduction in the medium to high frequency noise and a large unity-gain bandwidth (~550 khz). The task now became to design a controller which would preserve this noise performance yet improve the low frequency disturbance rejection.

The explanation for how the optimal controller works is easily seen in the frequency domain. It synthesizes a closed-loop system that possesses a proper, (relative degree identically equal to one) "1/s"-like loop transfer function. This is why the controller yields such large stability margins. In order to improve low frequency response, proportional gain must be increased. However, eventually time delay and klystron saturation preclude any further increase in gain. Because power and bandwidth are related, the unity-gain bandwidth is ultimately limited by the klytron's reserve power.

If the original physical system does not possess an integrator in the loop transfer function then, as in the traditional feedback method, an integral state must be augmented to the system. Physically this configuration is shown in Fig. 8. The high Q pillbox cavity in the outer loop approximates an integrator directly at rf. An alternative to the cavity is a resonant SAW device. The equations which describe this "P.I.D." controller is given by

$$\begin{bmatrix} dx/dt \\ dz/dt \end{bmatrix} = \begin{bmatrix} A & 0 \\ E^T & 0 \end{bmatrix} X + \begin{bmatrix} b \\ 0 \end{bmatrix} a$$

$$y = FX$$

where dz/dt defines the integrator state.

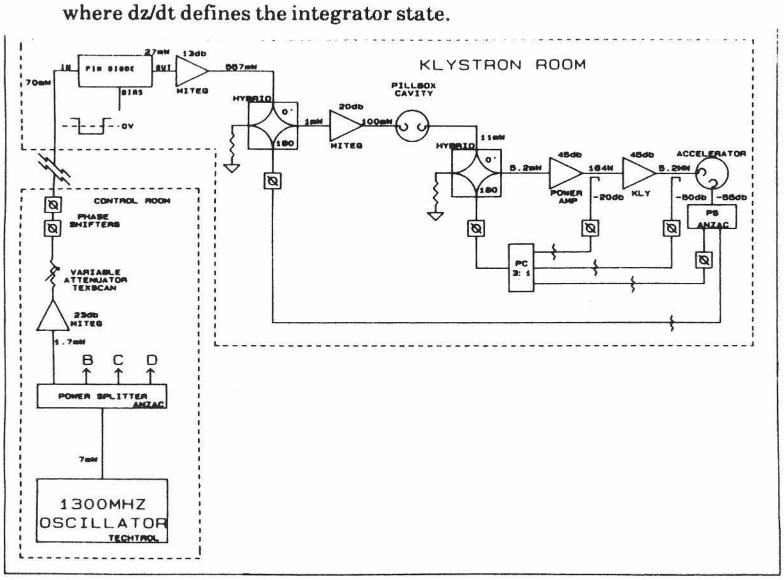

Fig. 8. "P.I.D" State Feedback design.

Figures 9 through 12 depict open- loop versus closed-loop performance. Optimization proceeds precisely the same way as before. With this new feedback system, the results todate are 0.25% amplitude droop, 0.03% amplitude noise, 0.5° phase droop, and 0.05° phase noise.

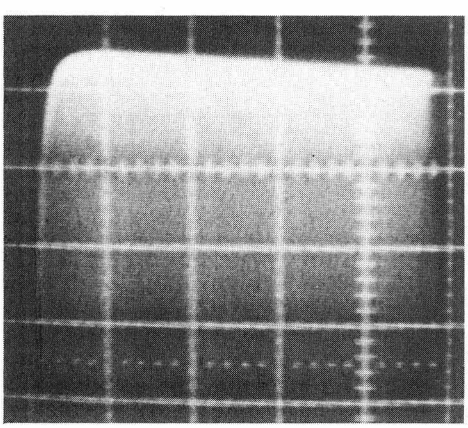

Fig. 9. Open-loop phase variation without beamloading. 2° and 20 µsec per division.

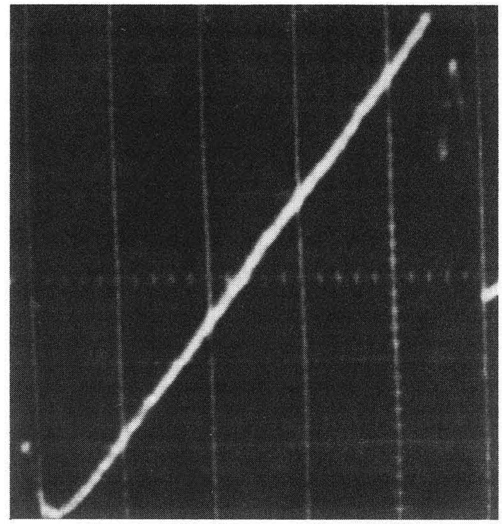

Fig. 10. Open-loop amplitude variation without beamloading. 12% and 20 µsec per division.

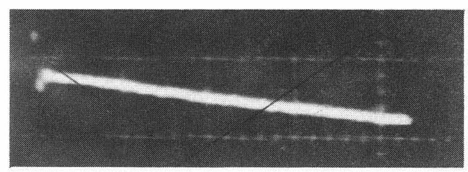

Fig. 11. Closed-loop phase variation without beamloading. 1° and 20 µsec per division.

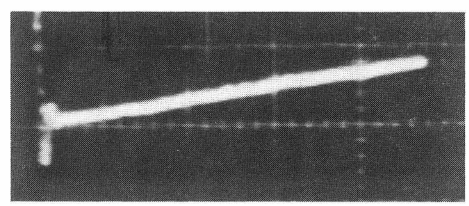

Fig. 12. Closed-loop amplitude variation without beamloading. 0.25% and 20 µsec per division

Conclusion

The first phase of our control research at LANL and UNM has been completed. Our effort has yielded a new controller with very low noise properties and large bandwidths. The beam-loading at the FEL is 50% and with a gain of 25 this results in a 2% steady-state error. For FEL operation it is far more important for the noise properties and transient error to be well controlled and to tolerate a small steady-state error. Future research will be directed at reducing this error. It is expected that with a pillbox cavity Q greater than 30,000, the steady-state error will be further reduced.

There are three major advantages of this new approach. The first is significant reduction in energy spread and energy slew. The second is the greatly reduced hardware. The third is that the feedback gains are implemented using only passive elements.

With the emphasis of robust control guiding the design of the feedback system, the synthesise technique yielded stable control systems. Robust stability and robust performance output feedback methods will be the subject of future experiments.

Reference

1. "Robust Control", Ed. P. Dorato, IEEE Press, 1987.
2. "Recent Advances on Robust Control", Ed. P. Dorato, IEEE Press, 1990.