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ROBUST CONTROL OF PARTICLE ACCELERATORS*

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Abstract

In this paper, we present a new technique for controlling the electric fields of an electron particle accelerator. This new scheme has greater stability and performance robustness than was previously achieved.

1. Introduction

One application of an electron particle accelerator is to drive a Free-Electron Laser (FEL). The FEL generates light by passing an electron beam through an alternating magnetic field, called an undulator, which produces coherent photons whose wavelength is proportional to the incident electron beam energy. The FEL performance depends critically on the properties of the incident electron beam. The equation of resonance for FELs is given approximately by

$$\lambda_L \approx \frac{\lambda_w}{2\gamma^2},$$

where λ_L is the laser wavelength, λ_w is the undulator magnetic field period, and γ is the relativistic mass factor of the incident electron beam. In order for the FEL to lase efficiently, theory projects that the fluctuations in γ must be less than the small-signal gain bandwidth, which is proportional to $1/(2N)$, N being the number of periods in the undulator. At Los Alamos, the present number of periods in the undulator is 40. In addition, experiments have shown that to generate light of a constant-intensity and wavelength, the energy fluctuations must be much less than $1/(2N)$ [1]. Our goal is to minimize the variations of γ , in order to give efficient, constant intensity, single-wavelength light. Fluctuations in $\gamma < 0.5\%$ has been chosen as our design goal. The factors that give rise to energy fluctuations are the variations in the accelerating electric fields and in the electron injector. This paper focuses only on controlling the effects of the electric fields. The consequences of fluctuations in the electron injector are less important and will be assumed negligible. These electric fields have both phase and amplitude components whose variations contribute to the

energy fluctuations, which in turn, directly produce variations in γ .

Previously, the control configuration was an output feedback with lead-lag compensation [2]. The electric field feedback signal from the accelerator is first resolved into its phase and amplitude components, each having its own control loop (Fig. 1). However, because the two loops are coupled, their separation can never be complete, nor is it necessary. Since the system that produces the electric fields contains nonlinearities and many uncertain parameters, the previous control system must be frequently tuned when operating conditions are changed. In addition, because of the simple structure of the compensator, the resulting performance is limited.

In this paper, we present a realistic model of the accelerator system that reduces the number of internal states to 3 as well as reducing the size of the uncertainties. The model shown in Fig. 2 is expressed to a first approximation by the linear state equation

$$dx/dt = Ax + Bu,$$

where A and B contain the system's parameters, $x(t)$ is the state vector, and u is the scalar input. In this model, some of the entries of the A and B matrices are uncertain. However, bounds on these entries are known.

The designed controller is of the state-feedback variety as opposed to the output-feedback controller used before. We find four major advantages of this new approach. The first is the significant reduction in energy fluctuation over the old control system. The second is the improved performance robustness over the previous technique. The third is the greatly simplified hardware. The fourth is that the feedback gains are implemented using only passive elements. This paper will report on both the analytic design and hardware implementation of the new robust control system. In section II we review the old design and discuss its limitations. Section III presents the design and implementation of the new controller, and section IV gives our conclusions.

2. The Classical Controller

To begin with, let us briefly review the previous technique. In Fig. 1 we show the old feedback system that produces and controls the accelerating electric fields, henceforth referred to as the amplifier chain.

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Fig. 1 Old LANL output-feedback scheme.

Fig. 2 State Feedback Controller.

The fundamental frequency of the accelerator is 1.3 GHz. Because reliable components (such as operational amplifiers) do not have appreciable gain at this frequency, and with the goal of regulating the amplitude as well as the phase of the accelerator, the output signal was resolved into its constituent components. A level detector is used to obtain the envelope of the accelerator output, thus giving a low-frequency signal. Likewise, a double-balance

mixer (DBM) is used as a phase detector and its output is also a low-frequency signal. Neither of the detectors are linear nor wideband for a large class of input signals. Up to the radio-frequency (rf) driver the amplifier chain is continuous wave (cw) and is operated in a pulse mode from the rf driver to the respective compensators, including the accelerator. Both control loops are unity feedback with the compensators in series with the plant. The external

inputs are the points labeled reference set point in Fig. 2. The references are both empirically determined; the amplitude is set by invoking the use of the level monitor and the phase is set by varying the manual phase shifter #1 while monitoring charge transport and/or energy. The manual phase shifter #2 is needed to adjust the line length of the 1.3 GHz reference phase in order to achieve negative feedback. The output of the DBM is the error signal for the phase loop. Both compensators are lead-lag filters (i.e., one pole and one zero experimentally tuned and determined). The electronically variable phase and amplitude devices are also nonlinear and have cross-coupling between the phase and amplitude signals, i.e., controller-produced phase modulations produce small amplitude variations, and vice versa. The result of this scheme is that the loop gain function has an order of at least six for the amplitude feedback and seven for the phase feedback. Both loops are very nonlinear, rendering accurate analysis very difficult if not impossible. The loop gain for this technique was 2 and the unity gain bandwidth was ≈ 200 KHz. However, even with these problems, the experimenters have been able to achieve sufficient control of the electric fields for optical wavelength and intensity stability of the FEL.

3. State Feedback Design

The purpose of the new design was to determine if significantly better optical performance could be obtained, constant controller tuning could be reduced, and electron-beam performance could be improved.

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, completely 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 accelerator. Including internal amplifier physical variables would be more than sufficient, and hence would form a nonminimal set. These outputs or states then precisely determine the complete behavior of the system.

The methods investigated were a pole placement design and an optimal state-feedback design with its well known stability robustness properties, i.e., infinite forward gain margin, 50% gain reduction margin, and at least $\pm 60^\circ$ phase margin. In addition, all dynamic control devices were discarded, leaving only the amplifier chain (Fig. 2). The modeling was purposely simplified (i.e., first-order variations only) in order to make the problem computationally as well as theoretically tractable. Both the amplifiers and the accelerator were modeled as first-order low-pass equivalent filters. 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 ($1.3 \text{ GHz} \pm 4 \text{ MHz}$) the gain curve is flat. Because the open-loop system is stable, off-line identification was performed, and the structured uncertainty in the plant model was reduced. The resultant nominal model without beam-loading disturbance is given by

$$dx/dt = \begin{bmatrix} -1.1 & 1 & 0 \\ 0 & -100.5 & 1 \\ 0 & 0 & -80 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 2 \times 10^{12} \end{bmatrix} u,$$

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

with uncertainty entering the A matrix and b vector as

$$\delta A = \begin{bmatrix} \pm 1.14 & 1 & 0 \\ 0 & \pm 5 & 1 \\ 0 & 0 & \pm 3.1 \end{bmatrix}, \quad \delta b = \begin{bmatrix} 0 \\ 0 \\ \pm 3.5 \times 10^{12} \end{bmatrix}$$

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

With simple eigenvalue assignment to $[-6.28, -100.5, -80]$ the feedback gains were -77 db , -97 db , and -116 db for k_1 , k_2 , and k_3 , respectively. (All db's are calculated in terms of power ratios.) These gains resulted in a return difference of 11 db or a loop gain of 12.5, a factor of 6 better than the previous scheme. The residual accelerator field fluctuations are now less than 0.2%. Figures 3 through 6 depict open-loop versus closed-loop with beam-loading disturbance.

Fig. 3. Open-loop phase variation with beamloading. 5 mV and 20 μsec per division.

Fig. 4. Open-loop amplitude variation with beamloading. 100 mV and 20 μ sec per division.

Fig. 5. Closed-loop phase variation with beamloading. 4 mV and 20 μ sec per division.

Fig. 6. Closed-loop amplitude variation with beamloading. 100 mV and 20 μ sec per division.

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

$$Q = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ and } r = 1 \times 10^8,$$

and the performance index was

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

The optimal control feedback gains were -73 db, -69db, and -40 db for k_1 , k_2 , and k_3 ,

respectively. Figures 7 and 8 show these results without beamloading. Different Q and r 's resulted in different performances, but the Q and r 's used in Figs. 7 and 8 were the most robust. The phase

Fig. 7. Closed-loop (phase) optimal control without beamloading. 5 mV and 10 μ sec per division.

Fig. 8. Closed-loop (amplitude) optimal control without beamloading. 100 mV and 10 μ sec per division.

margin was measured to be 75°. Although one of the amplifiers failed during one experiment, resulting in only half the normal forward gain, the control system maintained its stability due to its inherent robustness. 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. In addition, the klystron possesses a sector nonlinearity (normal operation of the accelerator precludes using this region). When the sector slopes were bounded by

$$\frac{1}{2} \leq \frac{P_{out}}{P_{in}} \leq \infty,$$

the state-feedback system was operated under optimal control conditions and figures 9 and 10 were the results. The closed-loop system has also been operated under a much stronger nonlinearity, resulting in large oscillations.

Implementation of this rf state-feedback control system took only 3 hours versus 240 hours for the old technique. Also, feedback system implementation costs have been reduced by a factor of 11. 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. Feedforward compensation will later be implemented in order to reduce to as near zero as can be measured any low-frequency variations, such as droop across the rf pulse.

Fig. 9. Closed-loop optimal control with sector nonlinearity and no beamloading (phase variation). 5 mV and 20 μ sec per division.

Fig. 10. Closed-loop optimal control with sector nonlinearity and no beamloading (amplitude). 100 mV and 20 μ sec per division.

4. Conclusion

To date, the new control system has been operating continuously since Oct. 11, 1989. It has not had any need to be adjusted (once set up) since that time. The original goals have all been met or exceeded, i.e., continuous tuning has ceased; loop gain has increased; the response has faster rise time with less overshoot; robustness against both known and

unknown modeling errors and induced plant parameter variations has been achieved; passive, invariant components have been implemented; and the cost has been reduced. Further research goals will be to include second-order variations and explore frequency domain controller design (e.g., H^∞ optimal control) with a state-space realization.

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Fig. 6. Closed-loop amplitude variation with beamloading. 100 mV and 20 μ sec per division.

Fig. 7. Closed-loop (phase) optimal control without beamloading. 5 mV and 10 μ sec per division.

Fig. 8. Closed-loop (amplitude) optimal control without beamloading. 100 mV and 10 μ sec per division.

Fig. 9. Closed-loop optimal control with sector nonlinearity and no beamloading (phase variation). 5 mV and 20 μ sec per division.

Fig. 10. Closed-loop optimal control with sector nonlinearity and no beamloading (amplitude). 100 mV and 20 μ sec per division.