CONTROL OF LINEAR ACCELERATOR NOISE IN THE LOS ALAMOS FREE-ELECTRON LASER (FEL)*

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Summary

FELs require tight control of the amplitudes and phases of the fields in two linear accelerator tanks to obtain stable lasing.[1] The accelerator control loops must establish constant, stable, repeatable amplitudes and phases of the rf fields and must have excellent bandwidth to control high-frequency noise components. A model of the feedback loops has been developed that agrees well with measurements and allows easy substitution of components and circuits, thus reducing breadboarding requirements. The model permits both frequency and time-domain analysis. This paper describes the accelerator control scheme and our model and discusses the control of noise in feedback loops, showing how low-frequency-noise components (errors) can be corrected, but high-frequency-noise components (errors) are actually amplified by the feedback circuit. Measurements of noise in both open- and closed-loop modes is shown and comparison is made with results from the model calculations.

Accelerator Feedback Control System

The feedback control circuits (Fig. 1) use both integral and proportional control in each of the amplitude and phase control loops. We recently completed a move of the klystrons and modulator tanks to reduce the feedback path delay as much as possible to improve the system frequency response. The round-trip signal-propagation time was shortened from ~400 to ~140 ns. The 140 ns represents 12° of phase shift at 250 kHz. Because the loop bandwidth is under 200 kHz, further reduction of the loop length would improve performance only slightly. The primary limitation to the loop bandwidth is the filtering action of the accelerator cavity. The Q of the accelerator is about 8000, which gives an ~2-μs fill time for the accelerator. In the feedback control-system operation, this fill time is equivalent to a low-pass filter with a 3-dB point of 80 kHz.

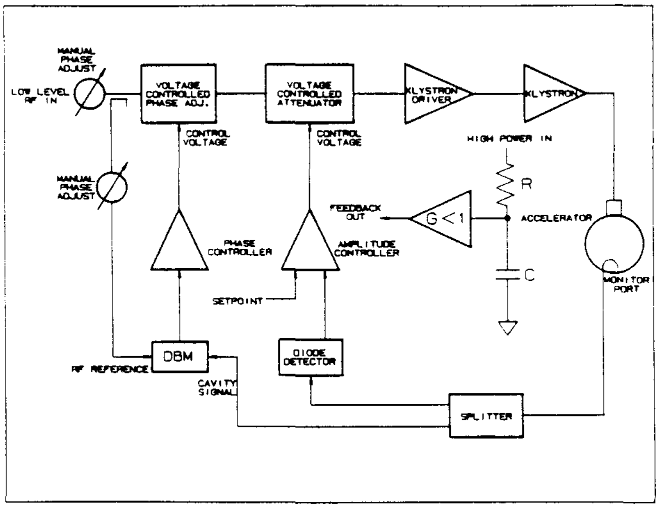

Fig. 1. Accelerator control system and circuit that models the accelerator cavity response. Cavity fill time $= \frac{Q}{\pi f_0} = RC$.

Model Description

If the accelerator cavity is modeled with individual circuit elements as a parallel R, L, C circuit, time-domain analysis must be done with enough resolution that each cycle of the rf is sufficiently represented (typically three points per cycle). To represent the FEL 100-μs pulse at 1300 MHz, 390 000 points would be required. Also, for both time- and frequency-domain analysis, the model must include modulator and demodulator circuits to convert the rf to and from appropriate low-frequency signals for use in the feedback circuits. A much simpler method in the case of feedback control circuits is to work entirely with the low-frequency signals. In this case, the cavity can be modeled as a simple RC integrator circuit with a time constant equal to the cavity fill time. The capacitor voltage represents the detected cavity field. Figure 1 shows the circuit used to model the cavity, where the gain element represents the feedback pickup loop.

For the RC circuit, the capacitor voltage E_c is given by $E_c = E_0(1-e^{-t/T})$, where $T = RC$. For a cavity, the envelope of the rf voltage[2] in the cavity is a function of rf frequency and the cavity Q; $E_{cav} = E_{source}\,[1-e^{-\omega_0 t/(2Q)}]$, and $2Q/\omega_0$ = fill time, where ω_0 is the angular cavity frequency. Thus, the RC model adequately represents the fill time of the cavity. Also, the RC model gives an accurate representation of the cavity phase shift and low-pass filtering for the feedback loop.

Each element in the feedback loop, from operational amplifiers to voltage-controlled attenuators, has been measured to determine its frequency-dependent properties. These components are then modeled with elements that accomplish basic s-plane (frequency-dependent) transfer functions with poles at the appropriate frequencies.

Agreement between the model and actual measurements has been very good. In one case, a prototype amplitude control circuit was built, and a Bode measurement (gain and phase plotted separately versus frequency) was made, which did not agree well with the model calculations. Further investigation revealed a defective operational amplifier that was giving excessive phase shift above 100 kHz. After replacing the operational amplifier, we obtained good agreement between the measurement and calculation. This was a case in which the model analysis enabled us to discover a subtle component failure.

Noise in Feedback Control Systems

The control of random fluctuations (noise) in the control loop of the accelerator has become very important in the Los Alamos FEL because of the sensitivity of the lasing to very small fluctuations in the electron beam parameters.[1] For the basic feedback loop (Fig. 2), the major noise sources are the high-power amplifier and noise generated in the accelerator cavity by fluctuations in electron beam current. These sources are reduced by (1 + LG), where LG is the system loop gain. For example, for noise, N, from the high-power amplifier (refer to Fig. 2):

$$LG = G_{cont} \cdot G_{amp} \cdot G_{cav} \cdot H, \qquad (1)$$

where G_{cont} = controller gain, H = feedback gain,
G_{amp} = amplifier gain and G_{cav} = cavity gain;

$$N_{ol} = N \cdot G_{amp} \cdot G_{cav}, \qquad (2)$$

where N_{ol} = noise in cavity, open-loop;

$$N_{cl} = N \cdot G_{amp} \cdot G_{cav} - N_{cl} \cdot (LG), \qquad (3)$$

where N_{cl} = noise in cavity, closed loop;

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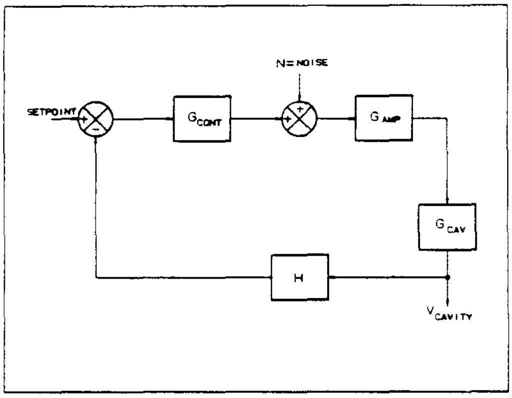

Fig. 2. Basic accelerator control loop.

$$N_{cl} = \frac{N \cdot G_{amp} \cdot G_{cav}}{(1 + LG)} \quad ; \text{ and} \tag{4}$$

$$\frac{N_{cl}}{N_{ol}} = \frac{1}{1 + LG} = \text{noise gain (CL/OL)} \tag{5}$$

This result, Eq. (5), shows that closing the loop reduces the original noise present in the open-loop mode by (1 + LG). At the point where LG has a 180° phase shift, the magnitude of LG is less than 1 as required for stability of the feedback loop. Because of the phase shift, however, (1 + LG) is less than 1; thus near the 180° phase shift (in the frequency domain), the closed-loop operation of the feedback system will show an increase in the amount of system noise when compared to the open-loop operation. The amount of increase depends on the system gain and phase margins. If the margins are small, the noise increase in the closed-loop mode can be quite large. If the gain margin is zero (violating the stability requirements for a feedback control system), the noise increase is infinite and the system is oscillatory.

Examples of the noise gain are seen in Figs. 3 and 4; Fig. 3 shows the detected field amplitude versus time in one of the FEL accelerators when operating in the open-loop mode. The signal has been offset and magnified to show the noise. The picture shows an ~0.1% peak-to-peak high-frequency noise level; Fig. 4 shows the same signal when operating in the closed-loop mode. The low-frequency noise (for example, the slope) has been reduced, but the high-frequency noise is much larger. The peak-to-peak level of noise in the closed-loop mode is ~0.3%.

Minimizing the Effects of Noise Gain

For a typical feedback system with a phase margin of 55° and a gain margin of 6 dB, this high-frequency noise gain can have a magnitude of 2 to 3 (6 to 10 dB). If the system gain is increased without changing the phase characteristics, the noise gain can become 5 or 10. This noise gain is a normal property of ordinary feedback systems. Its effect can be minimized by reducing the system gain to maximize the phase and gain margins or by increasing the bandwidth of the feedback system without reducing the phase or gain margins.

Reducing the gain reduces control of the low-frequency components (such as the slope caused by the capacitor bank droop). Therefore, reducing the system gain is usually not a suitable solution. When the system bandwidth can be increased without increasing the phase or gain margins, the noise gain will occur at a higher frequency. In this case, the actual level of noise in the accelerator would be reduced because of the filtering action of the cavity. Figure 5 shows the results of the model calculations on a bench setup. The only difference between the two calculations is the operational amplifier bandwidths. The system with the wider bandwidth operational amplifiers shows a lower peak noise gain (by about 20%) occurring at a higher frequency. Both the lower peak and the shift to a higher frequency would result in lower overall noise.

Noise Measurement Compared with Model Calculations

Efforts were made to digitize measurements, such as those in Figs. 3 and 4, and to perform Fourier transforms to show specifically which frequency band was increased in the closed-loop mode. The results could then be compared to similar results from the feedback model. The shot-to-shot noise varied too much, however, to allow much success with this method.

Somewhat better success was obtained with a feedback control system that was set up on the bench and configured much the same as the actual FEL control system using a 1-W amplifier driving a 1300-MHz cavity. Relatively good agreement between the two was obtained, but the variation in the shot-to-shot noise still caused a large spread in the noise-gain measurements.

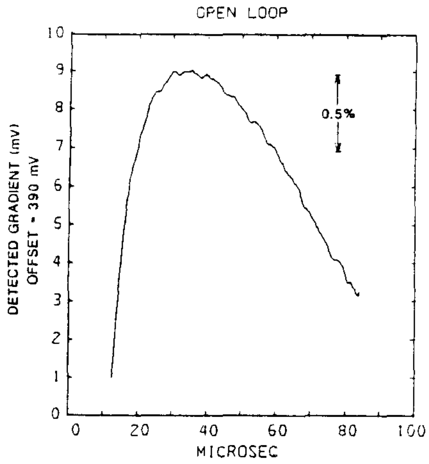

Fig. 3. Detected accelerator gradient in open-loop mode.

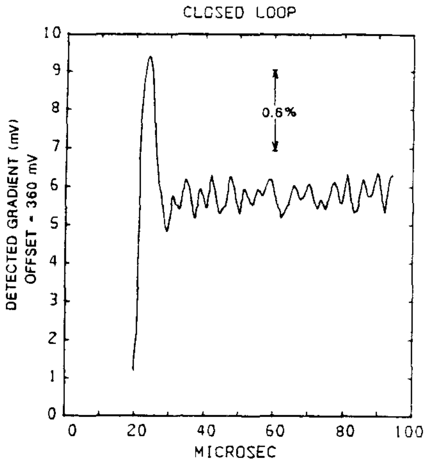

Fig. 4. Detected accelerator gradient in closed-loop mode.

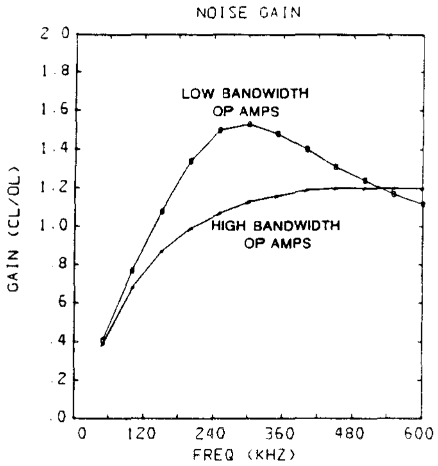

Fig. 5. Prototype control circuit. Calculations of noise gain showing that noise gain is reduced by wide-bandwidth operational amplifiers.

A different technique was then used that was successful. A signal generator applied a relatively large "noise" signal at a well-defined frequency into the amplitude controller (Fig. 6). The level of this signal in the cavity was then measured in both open- and closed-loop modes. The results of this measurement and the comparison with the model are shown in Fig. 7. Both methods show a peak noise gain of approximately 1.5 (3.5 dB) at 300 kHz.

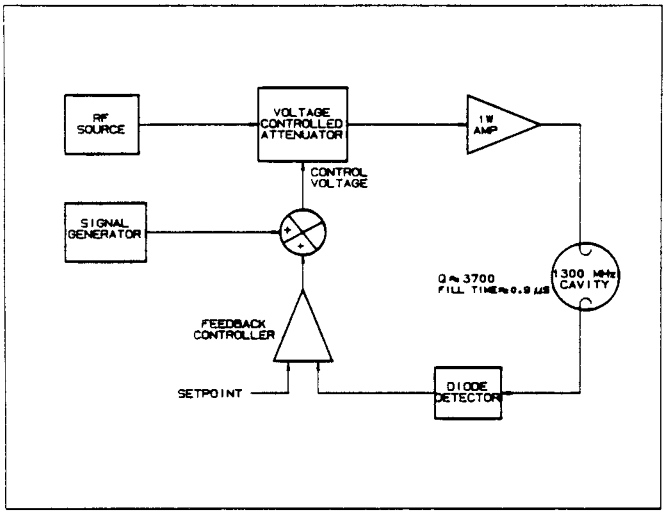

Fig. 6. Prototype control circuit. Block diagram of method to measure noise gain.

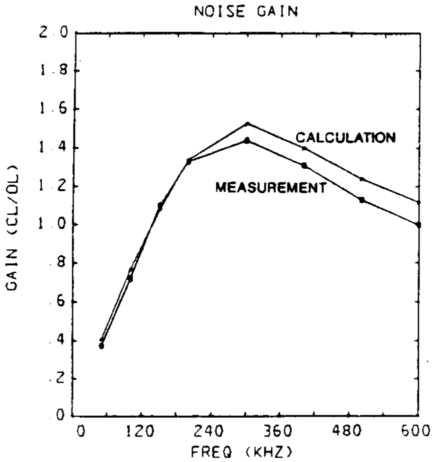

Fig. 7. Comparison of model calculations and measurements of noise gain made with setup shown in Fig. 6.

Noise-gain calculations for the present FEL accelerator control system are shown in Fig. 8. An upgraded control system under development uses wider bandwidth operational amplifiers than those used in the present system and has fewer operational amplifiers in series. Noise-gain calculations for the new control system in the present configuration are also shown in Fig. 8. The new control system was configured with approximately 1.5 times the loop gain of the present controller. In this mode, the peak noise gain has been reduced. Noise around 200 kHz is the predominant problem in our present operation. The new controller would give half as much noise at 200 kHz as the present system.

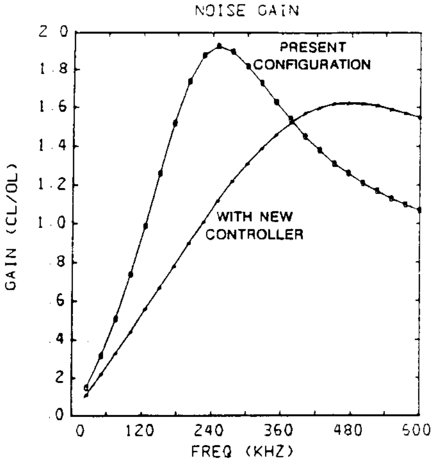

Fig. 8. Comparison of noise-gain calculations for the present accelerator control system and the control system with the newly designed control circuit.

Conclusion

Satisfactory operation of the FEL requires noise levels of around 0.1% or less. In general, standard closed-loop systems will reduce low-frequency noise, but they increase the high-frequency noise. As a rule of thumb, to maintain a noise gain of less than 1.5 (3.5 dB), the phase margin must be greater than 65° and the gain margin must be greater than 10 dB. If the system bandwidth can be improved to extend its operation to higher frequencies without reducing the phase and gain margins, the actual noise level can be reduced because of the filtering action of the cavity. We have developed a model of the feedback control systems that agrees well with experiments and allows extensive analysis of the feedback system.

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References

1. M. T. Lynch, R. W. Warren, and P. J. Tallerico, "The Effects of Linear-Accelerator Noise on the Los Alamos Free-Electron Laser," IEEE J. Quantum Electron. QE-21, 904 (1985).

2. E. L. Ginzton, Microwave Measurements, 429 (McGraw-Hill, New York 1957).