OPTIMAL ERROR MAGNITUDE ADAPTIVE CONTROL SYSTEM

by

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OPTIMAL ERROR MAGNITUDE ADAPTIVE CONTROL SYSTEM

INTRODUCTION

In a normal control system the controlled variable is activated by an error signal. To respond correctly, the error signal must consist of two pieces of information, magnitude and polarity. If polarity were not available, correct actuation would be difficult since the system could not determine which way to respond.

A system in which only error magnitude would be available is one in which the directly controlled variable could be peaked as in Figure 1. Hence, the error, which is the difference between the reference and the controlled variable, would always have the same polarity regardless of which side of the peak the operating point was on. The general control problem of such a system and its solution are discussed in this thesis.

Cosgriff (2, p. 133-135) first suggested the use of logical elements in conjunction with a servo motor to peak a variable. His controller needed to know the direction to the peak value and, therefore, the polarity of error. Furthermore, the controller hunted about the peak value constantly, and no stability analysis was presented to assure that the controller would not overshoot the peak and not return. Farber (3, p. 70-75) employed an analog computer and a mechanical system to follow the peak variation. Unfortunately, the analog computer introduced a delay into the system and caused the controller to overshoot the peak. Hence, his system also hunted about the peak value. Neither Cosgriff's nor Farber's works were known to the author before this thesis was nearly completed, although they would have been of little value.

During the author's summer employment with Lawrence Radiation Laboratory, he was assigned the problem of designing a control system which would maximize the beam energy of a linear accelerator. Upon investigation of the control problem the author discovered that only error magnitude was detectible and the beam energy could be peaked as in Figure 1. Because normal control concepts would not solve this problem, the author was compelled to consider it from a logical viewpoint, which was advantageous because the information appeared in pulse form. A controller was designed which did not hunt about the peak (as did the controllers of the authors previously mentioned) and could adapt to long-term variations in the peak value. Moreover, a quantative stability criterion was established for the controller-accelerator system which stated the conditions for stable operation.

THE GENERAL CONTROL PROBLEM

The optimal control problem is to peak the performance of a system even though the performance may be an indirectly controlled variable. As an example, an airplane autopilot may be designed to optimize response. However, to determine whether the response is optimized, the control system compares the actual and desired responses and, therefore, knows whether the actual response was too fast or too slow. Hence, while performance may be peaked because of the criterion established, the controlled variable is certainly not peaked but merely increased or decreased.

The optimization criterion would be directly controlled in a system as shown in Figure 1. Obviously, the polarity of error could not be determined by direct comparison of the controlled variable and the reference, because the reference is always greater than or at most equal to the controlled variable. Polarity must be determined from the measurement of other parameters. From a logical viewpoint such a system would respond to an error signal in the following manner:

1. Error magnitude is detected, and the system senses that it is either at point A or B, referring to Figure 1.
2. The sensing of polarity eliminates one of the two possibilities, and the system will respond correctly since its position relative to the peak value is known.

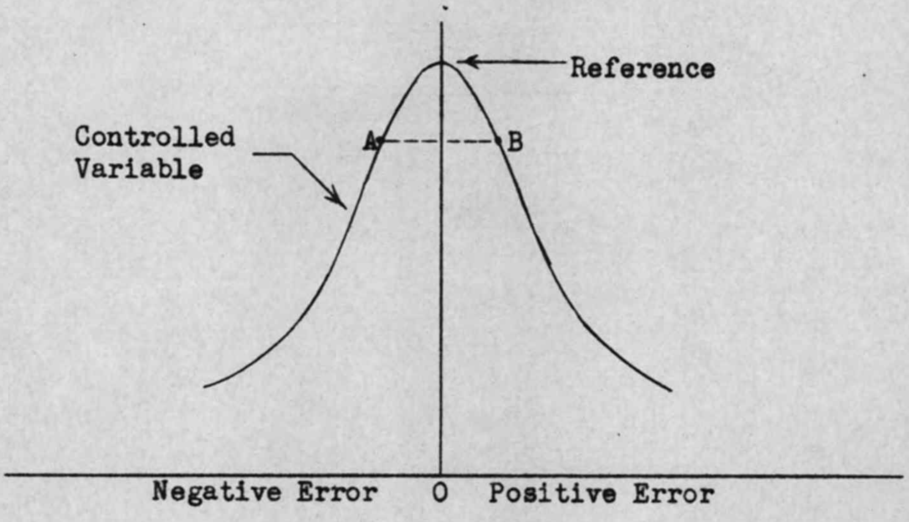

Figure 1.

A Peaking Controlled Variable.

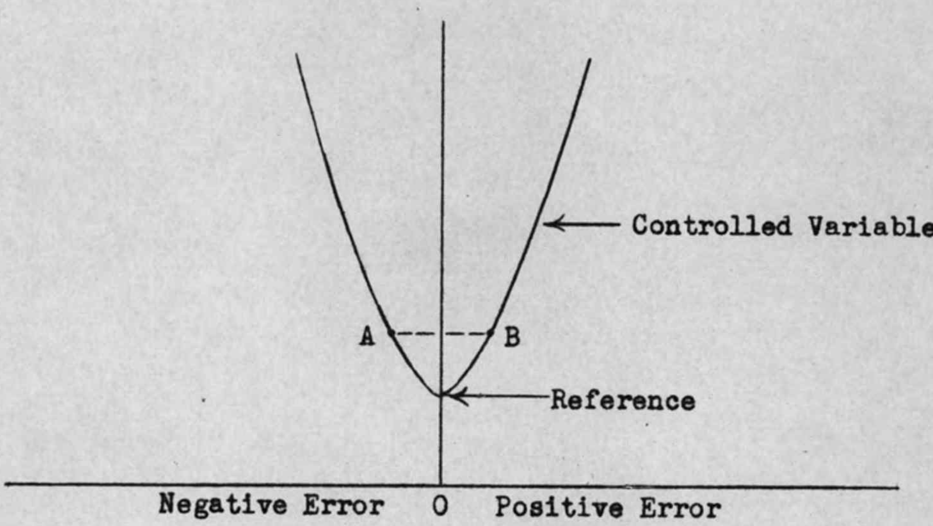

Figure 2.

A Nulling Controlled Variable.

The crux of the control problem rests with sensing polarity. Possibly, polarity could be determined with certainty from other parameter measurements, but more likely such measurements will only establish the polarity with a probability less than certainty. In this case the system could make a decision on its position based on this probabilistic error polarity, and the use of this information would increase the probability that its first decision would be correct. If the polarity were completely undetectible, the first decision could be the same every time or be perfectly random.

In the cases where polarity of error could not be determined with certainty, the control system must be able to recognize if its first decision is incorrect and make the necessary correction. For this type of system the logical sequence of possible events can be summarized as follows:

1. The system senses an error and makes a first decision as to whether it is at point A or B, which may or may not be based upon the use of probability.
2. As the system responds to its first decision, one of two mutually exclusive events will occur:
    a. The controlled variable will increase, meaning the first decision was correct.
    b. The controlled variable will decrease, meaning the first decision was incorrect.
3. At this time the system knows exactly where it is

and therefore which of the following it must perform:

a. If 2(a) is true, the direction of correction must be maintained until the peak value is reached.

b. If 2(b) is true, the direction of correction must be reversed and then continued in the reverse direction until the peak value is attained.

Rather than peaking a controlled variable, the problem may be to minimize the variable. Such a system is shown in Figure 2, and slight changes in the discussion on maximizing will give the logical sequence for minimizing a variable.

THE ACCELERATOR CONTROL PROBLEM

The linear accelerator[1] presents a control problem where the controlled variable can be either maximized or minimized and only error magnitude is detectible. The indirectly controlled variable is the beam energy, whose maximum is approximately 28 Mev, while the directly controlled variable is either the beam current pulse or the r-f excess power pulse, both shown in Figure 3. If the beam current is at its maximum or the r-f excess power at its minimum, the beam energy will be maximized. The repetition rates of the two possible controlled variables are the same, but the rate itself may vary from 10 to 400 pulses per second, depending upon the experiment for which the accelerator is being used. The pulse width is also the same for the two possible variables, but it may vary between 1.5 and 10 microseconds, again depending upon the experiment.

The beam current pulse was chosen to be controlled because of its better shape. The magnitude of the beam current is dependent upon the frequency f_o of the input r-f power and the resonant frequency f_r of the accelerator cavities as stated in Equation 1.

$$I(f_r, f_o) = I_{max} \exp \left[\frac{(f_r - f_o)^2}{\sigma^2} \right] \qquad (1)$$

where I_{max} is approximately 0.25 amperes, σ is a bandwidth factor of approximately 140 kc, and f_o and f_r are in the order of 2856 mc.

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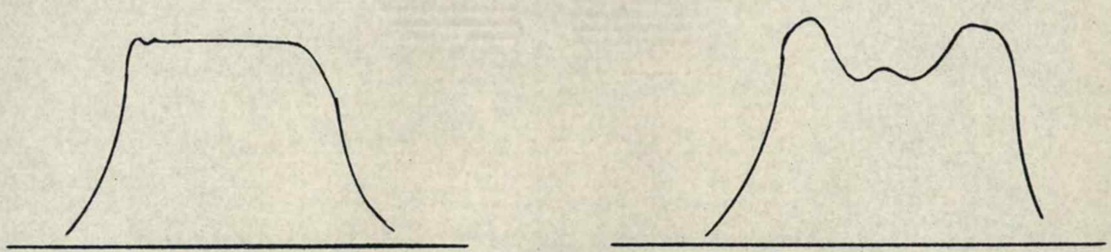
1 See Appendix for more detailed discussion of linear accelerator.



(a)
The Beam Current Pulse

(b)
The r-f Excess Power Pulse

Figure 3.

The Two Possible Controlled Variables of the Linear Accelerator.

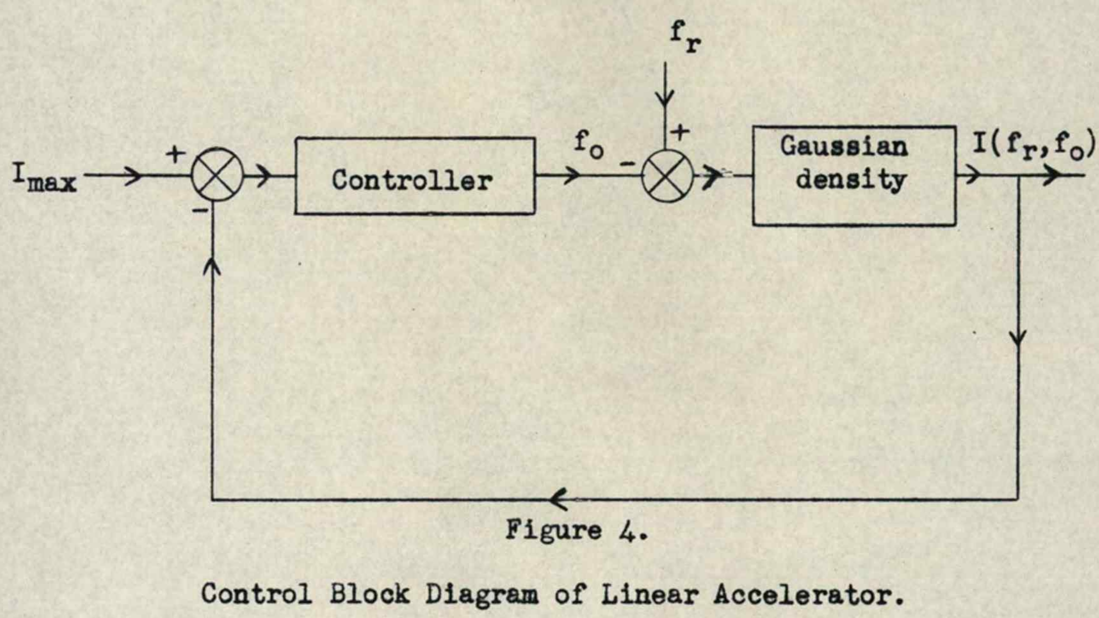


Figure 4.

Control Block Diagram of Linear Accelerator.

Equation 1 is a Gaussian density relationship and is a good approximation for the range

$$0.95\ I_{max} \leqq I(f_r,f_o) \leqq I_{max}\ . \qquad (2)$$

The inequality is not excessively restrictive since the current must be controlled within these bounds or the beam energy will be so low that the machine is considered "off the air". A difference between f_r and f_o of 100 kc will cause this drop.

The control block diagram of this regulating system is shown in Figure 4. The reference is I_{max}, the controlled variable is $I(f_r,f_o)$, the disturbance input is f_r, and f_o is the variable which is controlled to actually peak $I(f_r,f_o)$. From the block diagram it can be seen that the relative direction of drift of f_r and f_o cannot be determined by comparing I_{max} and $I(f_r,f_o)$. The changes in f_r are due to small changes in the mechanical structure of the accelerator cavities. Although a certain probability of the direction of drift could be established by measuring various parameters, it cannot be established with certainty. The drift of f_o could be detected, but the amount and expense of the equipment needed does not make it feasible to do so. Furthermore, unless a probability of the drift of f_r is established, no use could be made of any such measurement. Thus, the polarity of error cannot be determined. Therefore, the controller must match f_o to f_r and, in so doing, must be capable of making a decision and then reversing this decision if it proves to be the wrong one.

THE CONTROLLER

The first problem which must be solved is that of detecting changes in the beam current pulse height. Since there are variable pulse widths and repetition rates, pulse height discriminators are the best choice. The discriminators selected had a standard output pulse of 2.5 volts and 0.4 microseconds whenever there was an input pulse whose height was greater than or equal to the triggering level of the discriminator. The triggering levels could be varied, and the discriminators were sensitive to pulse height changes of at least 0.05 volt at the triggering level. This sensitivity was more than adequate for this particular application.

From the sequence of possible events listed on pages 5 and 6 at least two discriminators will be needed, one to detect error and the other to detect a wrong decision. Accordingly, the triggering level h_1 of the first discriminator D_1 was set slightly below I_{max}. The triggering level h_2 of the second discriminator D_2 was set below h_1. These values are illustrated in Figure 5. The actual difference between I_{max} and h_1 depends upon the noise, time constants, and delays in the system. In the accelerator the beam current pulse height varied a slight amount because of noisy circuits. Since the controller was not to attempt to correct for this noise but only control long-term drift, the difference between I_{max} and h_1 must be at least as much as the noise. The distance between h_1 and h_2 should be as small as possible, yet large enough so that if D_2 quits pulsing it will only be because of incorrect adjustment of f_o.

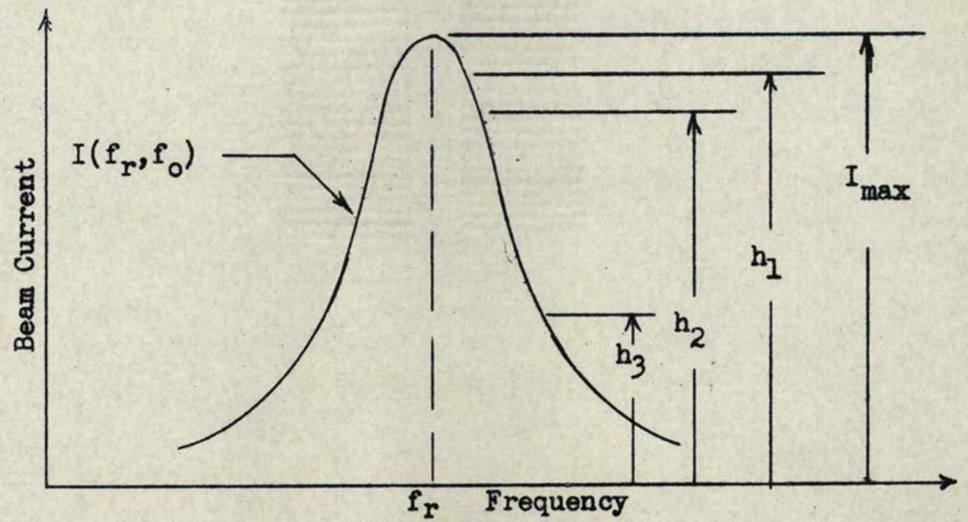


Figure 5.

The Controlled Variable, $I(f_r,f_o)$, Showing the Relative Magnitudes of the Reference and Discriminator Triggering Levels.

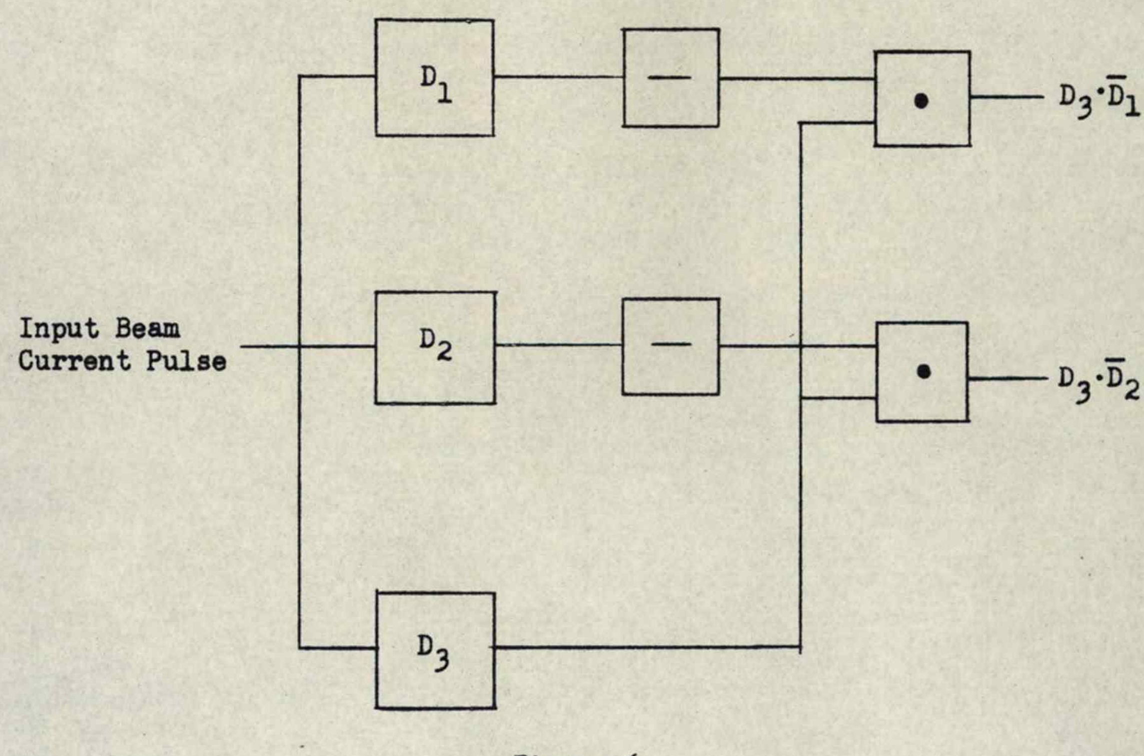


Figure 6.

The Block Diagram of Circuits to Mechanize Equations 4 and 5.

Although the two discriminators seem to give the correct information, they do so only if the system can distinguish between the times when there is no input pulse and a pulse below the triggering level of the discriminator. To do this a third discriminator D_3 was inserted with a triggering level h_3 set so that there will always be a standard output pulse whenever there is an input pulse.

Using logical notation the performance of the discriminators may be summarized as follows:

1. If $I(f_r,f_o) \geqq h_1$, then $D_1 = D_2 = D_3 = 1$.
2. If $h_2 \leqq I(f_r,f_o) < h_1$, then $D_1 = 0$ and $D_2 = D_3 = 1$.
3. If $I(f_r,f_o) < h_2$, then $D_1 = D_2 = 0$ and $D_3 = 1$.

The logical function,

$$D_3 \cdot \overline{D}_1 = 1 \,, \tag{4}$$

denotes the existence of an error although it does not fix the magnitude exactly, and the logical function,

$$D_3 \cdot \overline{D}_2 = 1 \,, \tag{5}$$

indicates that the first decision was wrong. The logic equations 4 and 5 are mechanized as "not-and" circuits. The schematic block diagram showing the connections between the three discriminators and the "not-and" circuits is Figure 6.

To allow the system to sense an error or wrong decision at all times, R-S (5, p. 121-126) flip-flops were used. The logic Equations relating the inputs to the flip-flops to Equations 4 and 5 are:

$$S_1 = D_3 \cdot \overline{D}_1 \tag{6}$$

$$R_1 = D_1 \tag{7}$$

$$S_2 = D_3 \cdot \overline{D}_1 \tag{8}$$

$$R_2 = D_1 \tag{9}$$

In these equations the S stands for set and the R for reset. Thus, if S_1 is true the first flip-flop, R-S_1, will be set to its true or "1" state, and if R_1 is true R-S_1 will be reset to its false or "0" state. A similar statement is true about R-S_2, the second flip-flop.

The final schematic block diagram of the controller is represented in Figure 7. The latter portion of the diagram, consisting of up-down counter, power amplifier, and stepping motor, has been used in similar applications at Lawrence Radiation Laboratory (6, p. 3), and the author claims no originality in its use. It was chosen because it coupled with the author's system with a minimum of extra circuitry and possessed excellent positional control. Concerning the operation of the counter and stepping motor, it is sufficient to say that the counter provides two inputs to the split-phase motor which are 180° out of phase. The field established by these inputs rotates only when the counter counts. The angle through which the shaft rotates for each count is dependent upon the number of poles of the motor as shown in Equation 10.

$$\Theta = \frac{2\pi}{p} \, , \tag{10}$$

where Θ is the angle of rotation in radians, and p is the number of poles in the motor which is 34. The effective angle Θ can be

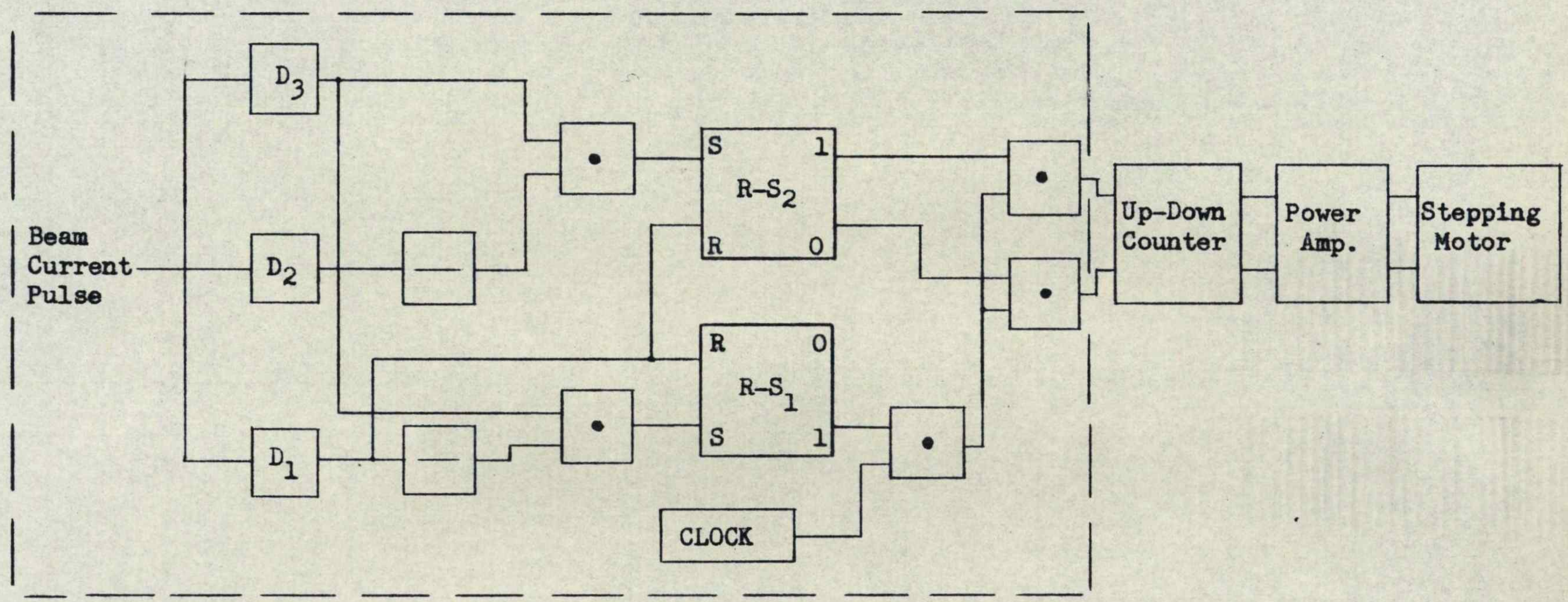


Figure 7.

The Controller

reduced even more by gearing between the motor shaft and the oscillator drive cavity which controls f_o.

The stepping motor will not respond to a repetition rate above 15 pulses per second, and the beam current repetition rate may often exceed this value. Therefore a clock was inserted with a repetition rate of 5 pulses per second to 500,000 pulses per second. The additional gating includes an "and" gate which $R\text{-}S_1$ may open to allow the clock to reach the next two gates. Only one of the other two gates is open at a time because $R\text{-}S_2$ will provide a true input for only one gate.

If a purpose of the controller were to minimize a variable such as the r-f excess power pulse, the only changes in Figures 5 and 6 are shown in Figures 8 and 9. Since the r-f excess power pulse cannot be reduced to zero but only minimized, the triggering level of discriminator D_3 would be set at h_3 so that it would always give a standard output pulse for any input pulse. The discriminators D_2 and D_1 have their triggering levels set at h_2 and h_1 respectively. The pulsing of D_2 denotes an error in the system, and the pulsing of D_1 denotes an incorrect decision. No portion of the controller, other than shown in Figure 9, would have to be changed in Figure 7.

Although this system uses pulses as information signals, either alternating or direct current could also be controlled. For alternating current the peak value repeats itself as with pulses. For direct current a sampler could be placed immediately

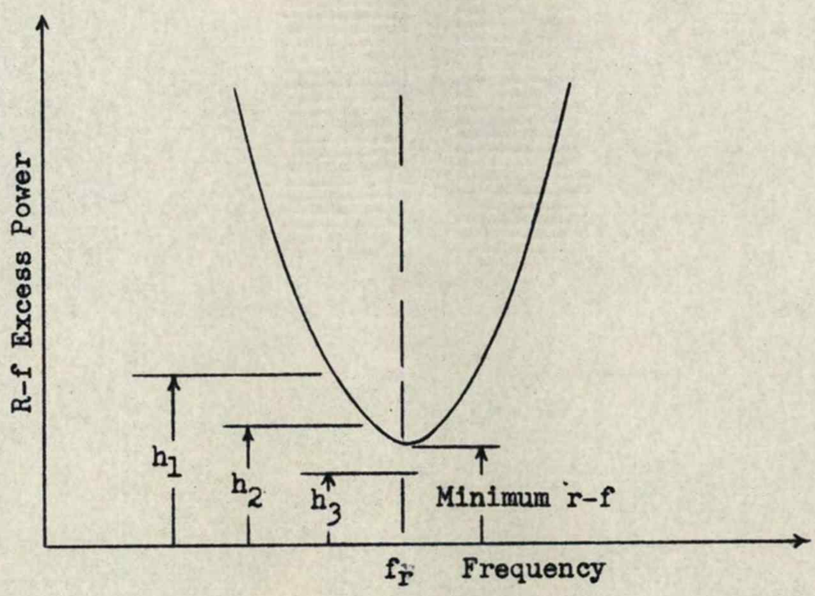


Figure 8.

The Alternate Controlled Variable, r-f Excess Power Pulse, with Triggering Levels of Discriminators Corresponding to Figure 9.

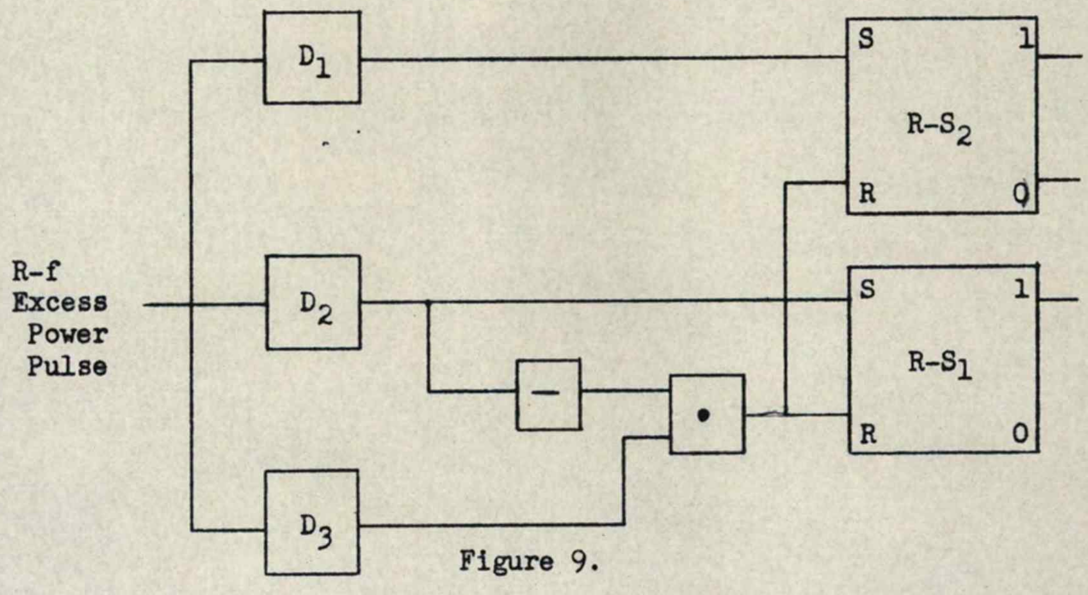


Figure 9.

The Modification of Figure 7 to Allow the Controller to Minimize the r-f Excess Power.

preceding the discriminators. Of course, the sampling rate must at least be equal to the clock rate.

A STABILITY CRITERION

The stability of the accelerator with the controller inserted is dependent upon the controller not overshooting the peak value because the system does not possess the ability to reverse itself a second time. The following stability criterion is a necessary and sufficient condition for the controller developed in the previous section. In the following section an adaptive controller is developed for which this criterion may not be necessary but will still be sufficient.

The rate at which f_o changes as a function of cavity shaft angular velocity is given in Equation 11.

$$\frac{\Delta f_o}{\Delta t} = \frac{250}{2\pi} \; \frac{\Delta \alpha}{\Delta t} \; [\text{kc/sec}] \qquad (11)$$

where 1 revolution of the cavity shaft will change f_o by 250 kc. The angle α is related to θ in Equation 10 by

$$\alpha = K \theta \quad [\text{rad}] \qquad (12)$$

where K is the gear ratio between the stepping motor shaft and the oscillator cavity shaft. The rate of change of θ is dependent upon the clock rate as follows:

$$\frac{\Delta \theta}{\Delta t} = \frac{2\pi}{p} f_c \quad [\text{rad/sec}] \qquad (13)$$

where f_c is the clock repetition rate. Combining Equations 11, 12, and 13

$$\frac{\Delta f_o}{\Delta t} = \frac{250K}{p} f_c \quad [\text{kc/sec}] \qquad (14)$$

The final factor affecting stability is the time it takes for

Δf_o to affect the output $I(f_r,f_o)$. This time T is dependent upon the repetition rate, the time constants and delays in both the accelerator and controller. Using Δf, as defined in Figure 10, a sufficient condition for stability is

$$\Delta f \geqq \left(\frac{\Delta f_o}{\Delta t}\right)\left(T\right) = \left(\frac{250}{p}\right)\left(K\right)\left(T\right)\left(f_c\right) \quad [kc] \quad (15)$$

If the above inequality holds, the system will be overdamped and stable. The gear ratio is the primary variable and would act as the variable gain of the system. To obtain tighter control h_1 would be raised thus reducing Δf. Hence, K would have to be reduced to satisfy the inequality. Thus speed of response and precision of control are opposed to one another.

The factors mentioned in Equation 15 are known within specified limits as follows:

1. The number of poles of motor, $p = 34$.
2. The clock repetition rate lies in the range $5 \text{ pps} \leqq f_c \leqq 15 \text{ pps}$.
3. The gear ratio is the variable gain of the system to be adjusted for stable operation.
4. The time T is the most difficult factor to determine, and a discussion of its approximation follows.

The time T is dependent upon a number of time lags and constants in both the accelerator system and the controller. Equation 16 numerates the various times involved.

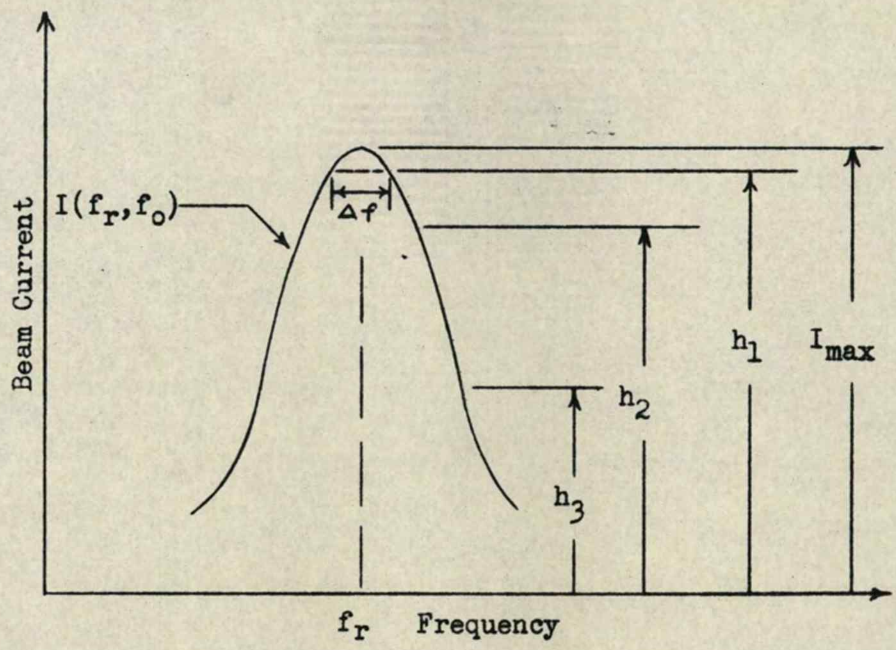


Figure 10.

The Modification of Figure 5 to Illustrate the Definition of Δf.

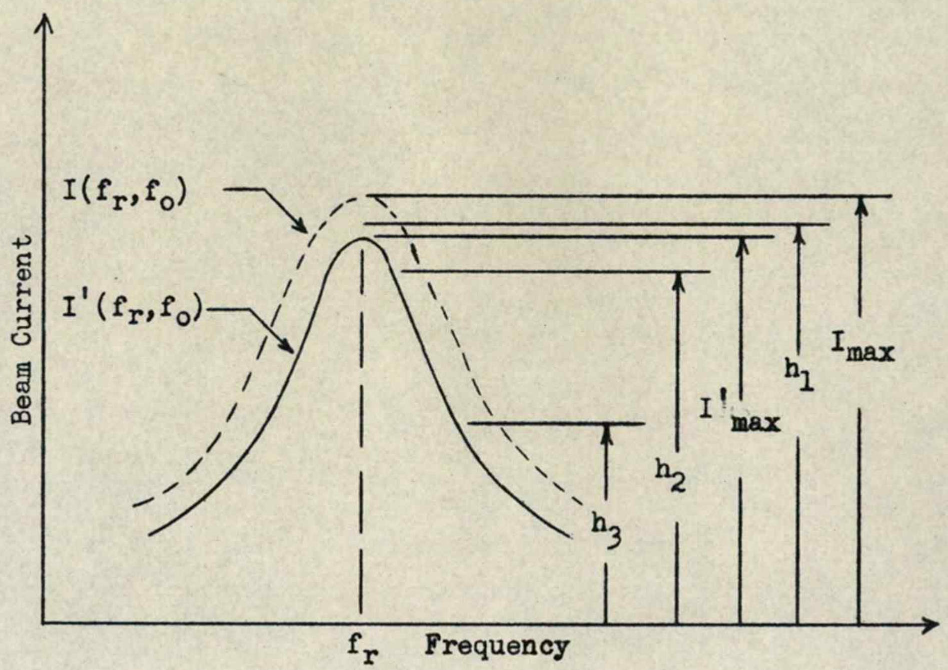


Figure 11.

Illustration of Possible Long-Term Variation of Controlled Variable and Reference.

$$T = T_1 + T_2 + T_3 + T_5 + T_6 + T_7 + T_8 + T_9 + T_{10} + T_{11} \quad (16)$$

The following table defines each time in Equation 16 and gives an order of magnitude for its value.

TABLE I.[2]

Definition and Order of Magnitude of Terms in Equation 16.

T_1	Transit time of electron beam through accelerator tubes to detector.	10 nsec.
T_2	Time constant of detector.	20 nsec.
T_3	Transport lag from detector to discriminators.	Between 2 μsec. and 0.1 μsec.
T_4	Time constant of oscillator drive cavity.	7 μsec.
T_5	Transport lag from oscillator to TWT amplifier.	Same as T_3.
T_6	Time constant of TWT amplifier.	50 nsec.
T_7	Transport lag from TWT amplifier to power klystrons.	Much smaller than T_3 because of much smaller cable lengths.
T_8	Pulse period of power klystrons.	Between 0.1 sec and 0.0025 sec.
T_9	Transport lag from power klystrons to accelerator tubes.	Same as T_7.
T_{10}	Time constants of discriminators and logic circuits including counter.	2 μsec.
T_{11}	Time constant of stepping motor.	0.05 sec.

2 See appendix for more detailed discussion of linear accelerator.

The significant time delays in the system are therefore the pulse period of the accelerator T_8 and the time constant of the stepping motor T_{11}. The other significant time delay in the system is the clock repetition rate which has already been included in Equation 15.

THE ADAPTIVE CONTROLLER

One implicit assumption concerning the accelerator control problem was that I_{max} was constant except for small variations due to noise. If I_{max} were to have large long-term variations, the controller in Figure 7 would not function correctly. Referring to Figure 11 where the peak value I'_{max} has dropped below h_1, the controller would sense an error and eventually drive over the peak because D_1 would not pulse. Furthermore, the direction of adjustment would not be reversed, and $I'(f_r, f_o)$ would be driven to a minimum. To meet this problem two changes are necessary. First, the controller must be capable of reversing its direction more than once. Second, the reference, meaning h_1 and h_2, must be capable of being lowered.

The logical sequence of events which the controller will encounter and must be able to perform are:

1. An error is detected, and the controller responds as stated in the controller section.
2. One of three mutually exclusive events then occurs:
   a. The controller made the correct decision, and $I(f_r, f_o) \geqq h_1$ is attained.
   b. The controller made the wrong decision, and $D_3 \cdot \overline{D}_2 = 1$ becomes true, and the controller reverses.

c. The controller made the correct decision, but $I'_{max} < h_1$ is true (Figure 11), and therefore $D_3 \cdot \overline{D}_2 = 1$ becomes true, and the controller reverses.

[Note that the controller cannot distinguish between 2(b) and 2(c)].

3. If 2(b) is true, one of two mutually exclusive events will occur:

   a. $I(f_r,f_o) \geqq h_1$ is attained, and the controller stops adjustment.

   b. $I'_{max} < h_1$ is true, and $D_3 \cdot \overline{D}_2 = 1$ will again be true.

4. If 2(c) is true, the condition $D_3 \cdot \overline{D}_2 = 1$ will again become true.

5. If 3(b) or 4 is true, the controller must reverse again and must also lower the reference because it is now certain that $I'_{max} < h_1$. The reduction of h_1 and h_2 must be done before the controller sweeps past the peak value of $I'(f_r,f_o)$ again.

6. This sweeping must be continued with subsequent lowering of h_1 and h_2 until $I(f_r,f_o) \geqq h_1$ is achieved.

The modifications of the portion of the controller in the dotted block in Figure 7 which are necessary to adapt to variations of I_{max}

are shown in Figure 12. To best understand the operation of the adaptive controller, consider the following sequence of events:

The equilibrium condition is

1. $R\text{-}S_1$ is reset.
2. $R\text{-}S_3$ is set.
3. J-K is reset.
4. $R\text{-}S_4$ is reset.

If an error occurs under the condition of Figure 11,

1. $D_3 \cdot \overline{D}_1 = 1$ will initiate adjustment.
2. $D_3 \cdot \overline{D}_2 = 1$ will occur.
3. The J-K flip-flop will change state on the first pulse because both $D_3 \cdot \overline{D}_2$ and $R\text{-}S_3$ are true inputs to "and" gate #1.
4. This same pulse travels through the delay, resets $R\text{-}S_3$ (closing "and" gate #1) and sets $R\text{-}S_4$ (opening "and" gate #2).
5. Subsequent pulses for the condition $D_3 \cdot \overline{D}_2 = 1$ will not cause the J-K flip-flop to change state because "and" gate #1 will remain closed until $D_2 = 1$ is true.
6. The controller will sweep until D_2 becomes true and continue until the condition $D_3 \cdot \overline{D}_2 = 1$ again occurs.
7. This time the first pulse will cause the J-K flip-flop to again change state and reset $R\text{-}S_3$

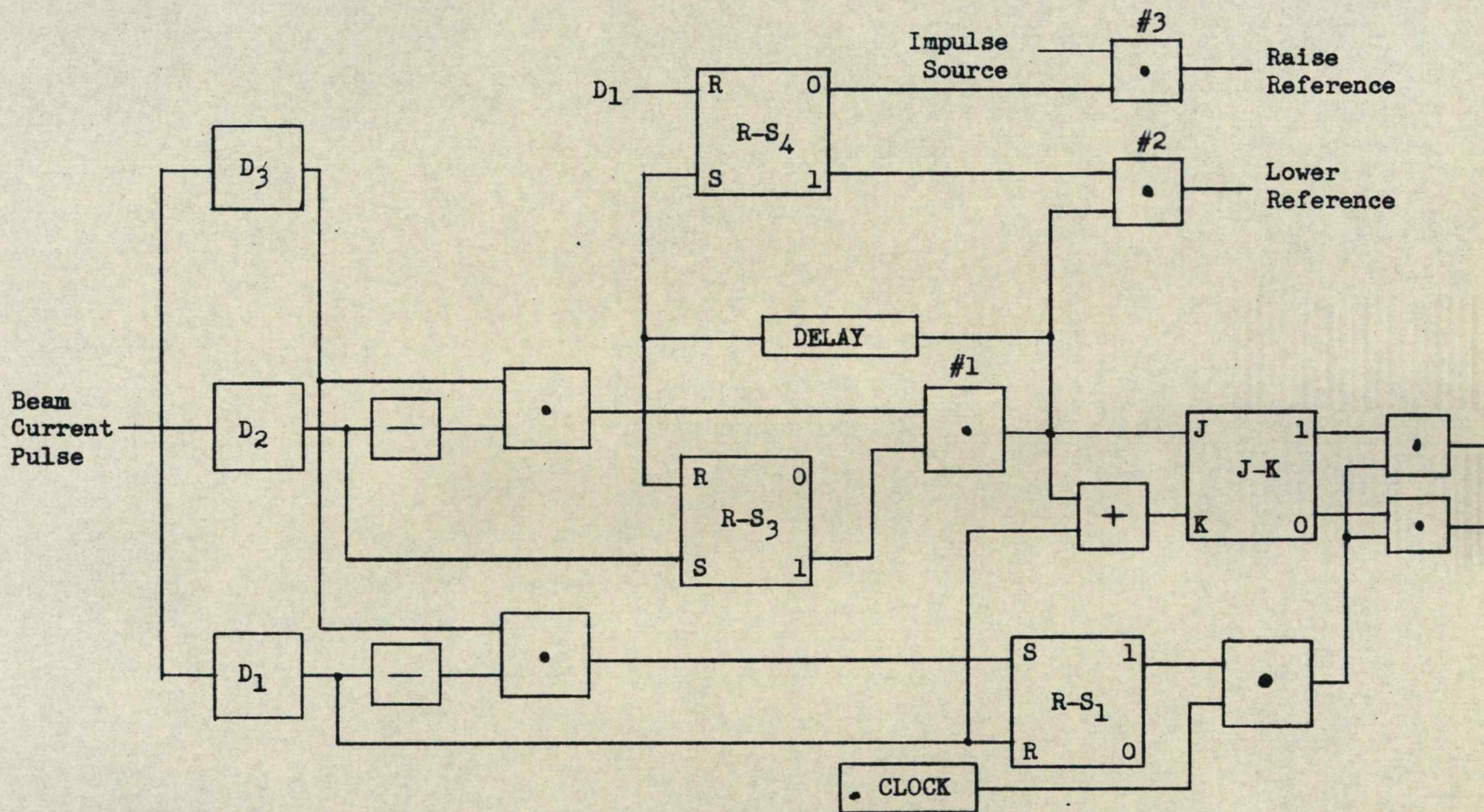


Figure 12.

The Adaptive Controller

as before, and will go through "and" gate #2 because $R\text{-}S_4$ is in its true state from the pulse mentioned in items 3 and 4 above.

8. The output pulse of "and" gate #2 tells the controller to lower h_1 and h_2.
9. Items 6 through 8 may occur again until $h_1 \leqq I'_{max}$ is attained.

The drift of I_{max} may be upward as well as downward, and furthermore, the controller must be capable of following I_{max} up after it has gone down. The difficulty in detecting this upward drift lies in the possibility that, although the peak value may rise, the operating point may not change. This problem can be solved by inserting "and" gate #3 whose inputs are the "0" side of $R\text{-}S_4$ and an impulse source. Therefore, the gate is closed whenever the controller is adjusting f_o because $I(f_r,f_o) < h_1$.

The impulse repetition rate is such that an impulse occurs when a variation of I_{max} is expected. Since this variation is in the order of many minutes, the impulse repetition rate could be determined. If the impulse goes through "and" gate #3, the controller raises h_1 and h_2 a specified unit. If the system can be peaked to this higher value, the controller will do it. If not then the system will lower the h_1 and h_2 the same unit, and the process will continue at this level until either $I(f_r,f_o) < h_1$ or the next impulse occurs.

Therefore, the adaptive controller will obtain the maximum beam energy that can be achieved from the accelerator. There are tolerances, of course, and the stability criterion established in the previous section is certainly applicable to this adaptation.

CONCLUSIONS

This paper proves the practical feasibility of controlling a process in which the polarity of error is not detectible. This proof is illustrated not only from a logical viewpoint but also with a controller which was actually constructed. This controller, in Figure 7, was designed and built by the author during his summer employment at Lawrence Radiation Laboratory and performed as predicted, although it was not actually coupled into the accelerator system at the time of the author's termination.

The stability criterion is an important and necessary contribution because other authors who have suggested actual solutions to this type of problem have neglected to either consider or mention it. Obviously, no system will function correctly unless some stability criterion is met even though the designer may not be aware of this need.

The extension of the original controller to an adaptive one is not only of value to the accelerator control problem, but the concept should be useful to other error magnitude control problems. This type of controller has many advantages in that it can control a-c, d-c, or pulse error magnitude processes for much less cost than would be necessary to detect polarity of error or its probability.

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APPENDIX

THE LINEAR ACCELERATOR

The linear accelerator is a machine which accelerates electrons along a straight line to energies of 30 Mev or more. The accelerator consists mainly of an r-f oscillator, a TWT amplifier, a power klystron, and the accelerator tube, all shown in Figure A1.

The r-f oscillator consists of a TWT amplifier with a machanically adjustable cavity in its feedback loop which causes the combination to oscillate at a frequency f_0 near 2856 mc. The cavity can be adjusted to cause the continuous wave output of the oscillator to vary a few hundred kc on either side of 2856 mc.

The r-f oscillator drives a TWT amplifier through 100 feet of coaxial cable which connects the two elements. The output of the TWT amplifier consists of intermittent bursts of r-f power which are obtained by turning the cathode on at periodic intervals even though the grid input from the oscillator is continuous wave. The output is said to be pulsed. The TWT amplifier is connected to the power klystron through 10 feet of coaxial cable. The power klystron is an r-f power amplifier with a maximum pulsed output of 5 megawatts. The connection between the klystron and accelerator tube is through a short length of coaxial cable.

The accelerator tube is a cylindrical structure with iris diaphragms inserted as shown in Figure A1. Electrons, which enter one end of the tube in bunches, are accelerated down the tube to the target. As the electrons leave the tube they pass a probe which detects the positive envelope of the r-f signal accompanying

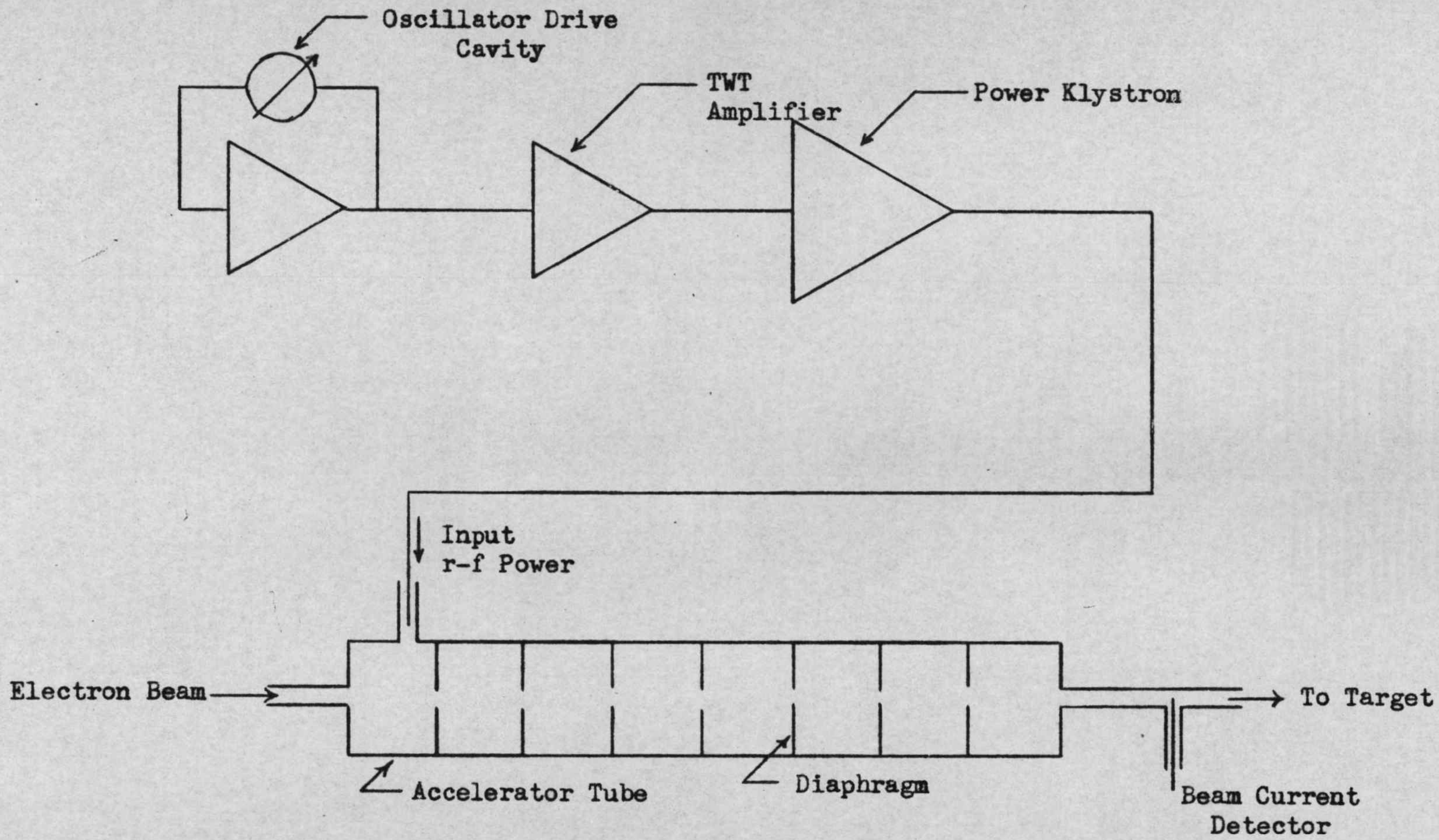

Figure A1.

Schematic Diagram Showing Pertinent Features of Linear Accelerator.

them. This envelope is the beam current pulse referred to in the body of this thesis.

The diaphragms of the tube are equally spaced and act as reactive loads in the tube for the input r-f power. Since the tube acts as a terminated waveguide, reflections occur, and, if the frequency f_o of the input r-f power equals the resonant frequency f_r of the tube, a standing wave pattern will be established with nodes located at the diaphragms. If f_o does not equal f_r, the reflections will cause a perturbing field which disperses the bunched electrons into a continuous beam. Since the diaphragms act as loads, they consume power, and the dissipated heat changes the diaphragm structure slightly. This structural change causes the resonant frequency f_r to also change. Consequently, f_o no longer equals f_r, and the nodes of the input r-f power do not occur at the diaphragms. A reduction in the beam current magnitude results.

A probability of the direction of drift of f_r could have been determined by making some measurements of the temperature of the accelerator tube structure. As the tube is being heated, f_r will usually change in one direction, and, as the tube is cooled, f_r will usually change in the opposite direction. The cooling is accomplished by a very loosely controlled water system which allows moderate variations to occur before actuation.