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A Theoretical and Experimental Analysis of Delay Circuits

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TSAI — DELAY CIRCUITS

A THEORETICAL AND EXPERIMENTAL ANALYSIS OF DELAY CIRCUITS

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I. GENERAL STUDY OF DELAY CIRCUITS

1. Definition

A delay circuit is a circuit which produces rectangular pulses of specified duration.

A rectangular pulse consists of three parts: first, a sudden rise of voltage; second, remaining a constant voltage during a certain time interval; and third, a sudden drop of voltage to its original value.

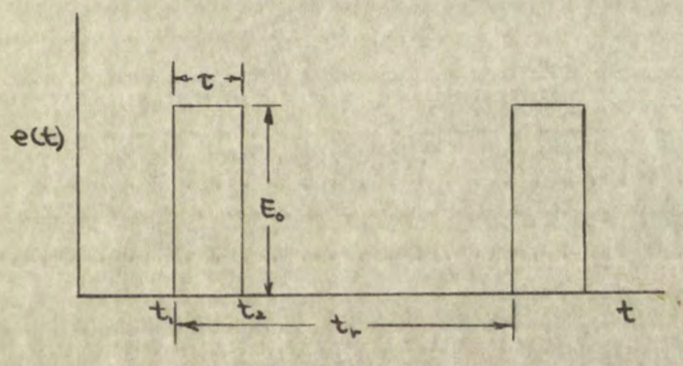


Fig 1. Rectangular Pulses

If the sudden rise of voltage at t_1 is produced by a certain sudden action of a circuit previous to the pulse circuit, the sudden drop of voltage at t_2 can cause another circuit to produce a sudden action. Thus, the second action is produced by the first action at a time $(t_2 - t_1)$ later. Or we say the action is delayed. Thus the pulse circuit can be termed as a delay circuit.

Referring to Figure 1., τ is the pulse duration; t_r the repetition period; and f_r (the reciprocal of t_r) the repetition frequency.

2. Application of Delay Circuit

The delay circuit has many applications in radar system. This Thesis will discuss a few of them.

First, Consider the application of a delay circuit to the indicator circuit. Consider the circuit in Figure 2. If $e_c=0$, the tube conducts in the static state, e_b is equal to the product of the static plate current and the static plate resistance. This voltage is very small. When a large negative voltage e_c (according to the polarity shown in the figure) is suddenly applied, the tube is suddenly cut off. But because of the condenser C the voltage e_b cannot rise to the value E_{bb} suddenly. The voltage will rise according to an exponential curve. Now when the negative e_c is removed, the tube conducts. Because of the presence of the condenser C the voltage e_b will drop again according to an exponential curve. We can choose the value of the capacitance C such that at the beginning, the first exponential curve is almost a straight line. Thus a saw-tooth voltage is obtained. The idea is clearly illustrated with the help of the waveform shown in Figure 3. The main operation is due to the grid voltage e_c which can be supplied by a delay circuit.

Now, in radar operation we first send out a signal pulse. The echo pulse comes back after a certain time. This echo pulse is then shown in the indicator which is essentially a cathode-ray tube. Between the echo pulse and the second transmitted pulse it is desirable to cut

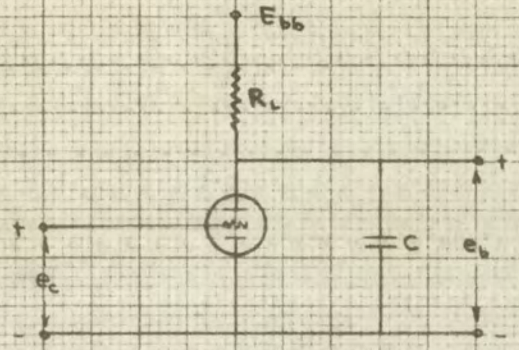


Fig 2. Saw-tooth Generator
Circuit Diagram

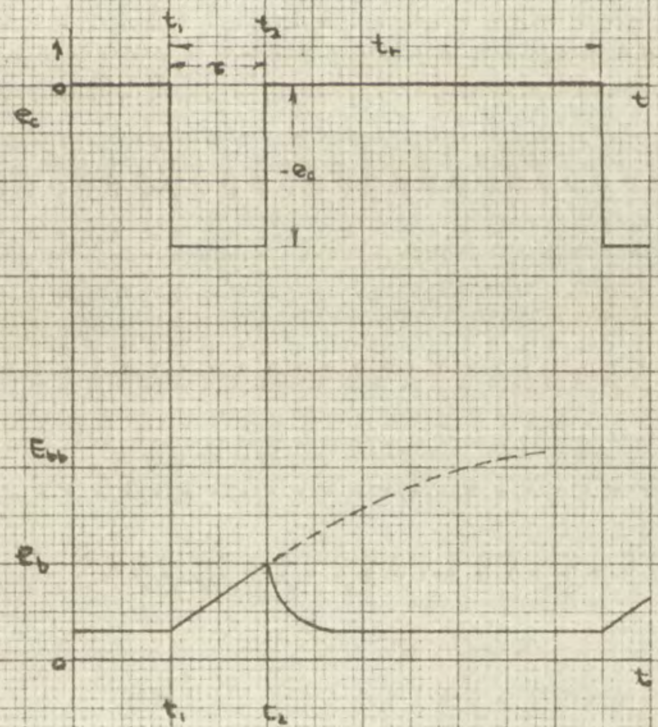


Fig 3. Saw-tooth Generator
Wave Form

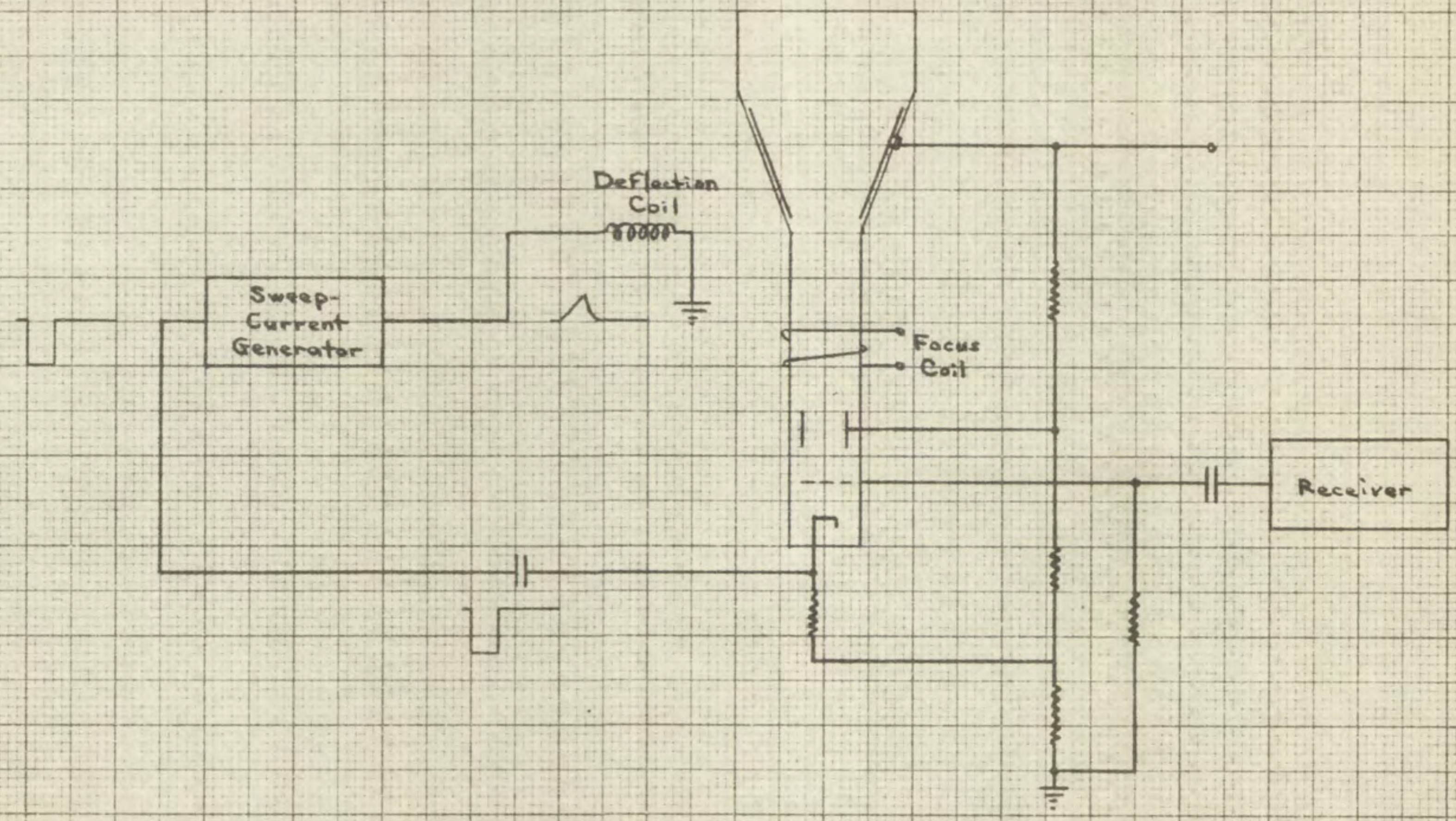


Fig. 4. Application of Delay Circuit to the Indicator Circuit

off the sweep since nothing is expected to happen. This is performed by using the delay circuit to produce the saw-tooth sweep voltage as shown in Figure 4. At the same time thepulse is used to intensify the electron beam during the sweep or even cut off the electron beam between sweeps which is the case as shown in Figure 4.

Next, Consider the application of the delay circuit in a range marker. Consider, first of all, the circuit in Figure 5. Before applying the pulse the tube is biased at zero voltage, therefore it conducts in the static state. The voltage e_b is then constant. When the pulse is applied, the tube is cut off. The cathode circuit which consists of an inductor and capacitor, acts then as a LC free oscillating circuit and begins to oscillate. The damping effect, however, can be made very small. At the end of the pulse, the tube conducts again. There is again a sudden change in the voltage across the LC circuit and another oscillation takes place. However the conducting tube is equivalent to a resistance shunted across the LC circuit. Therefore the oscillation is damped very fast. The waveform is illustrated in Figure 6.

Consider, now, the circuit in Figure 7, which is simply an over driven amplifier. The grid is biased at zero voltage and the signal swing is much larger than the cut-off voltage. We can get the waveform of the plate current by examining the grid voltage-plate current characteristics. When the grid voltage is equal to the cut-off voltage,

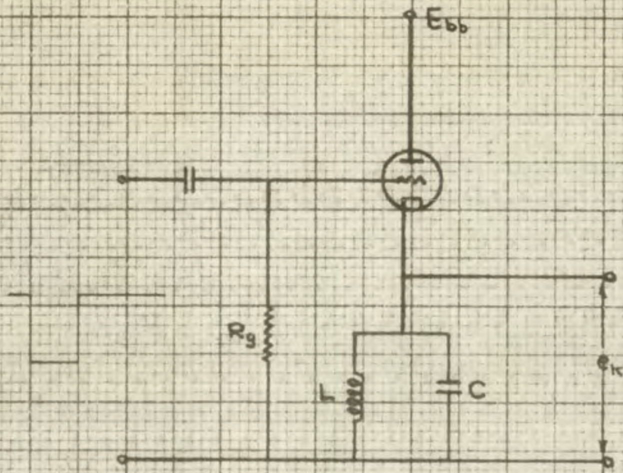


Fig. 5. Circuit Diagram.

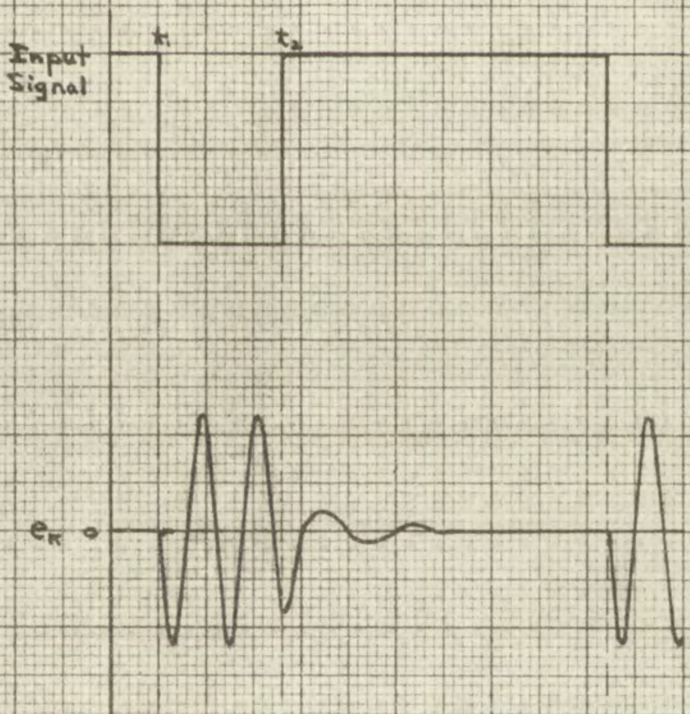


Fig. 6. Waveform for the Circuit Shown in Fig. 5.

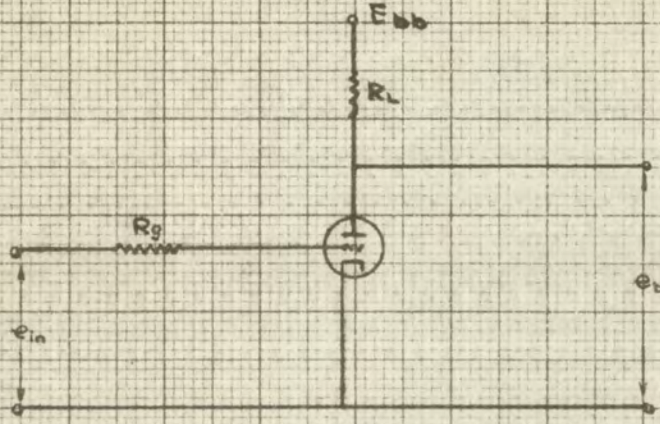


Fig. 7. Circuit Diagram

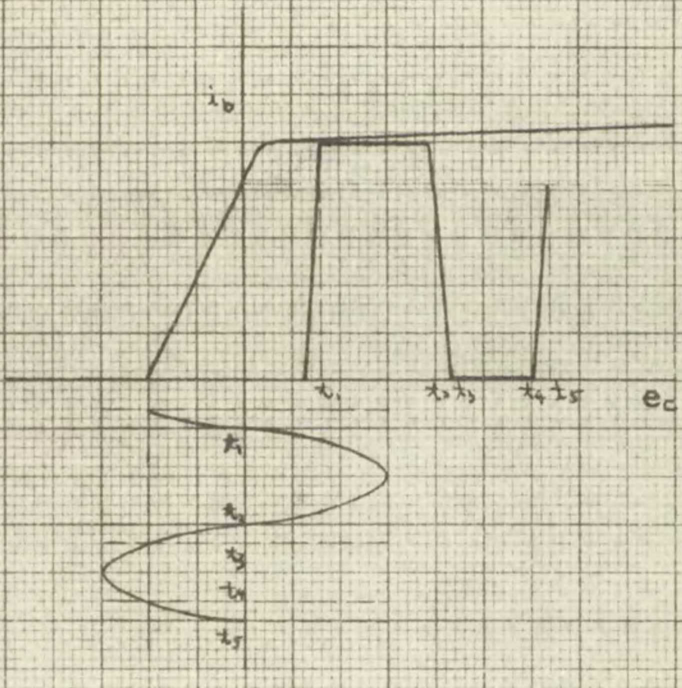


Fig. 8. Grid voltage - Plate current
Characteristic

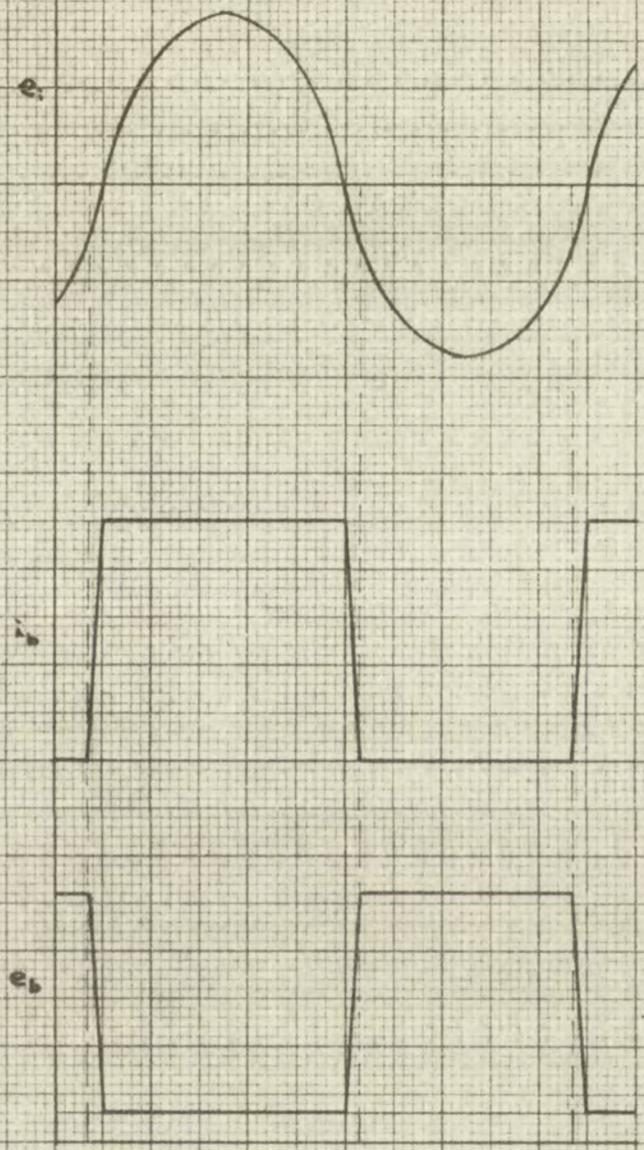


Fig. 9. Waveform for the Circuit shown in Fig 7.

plate current is zero. The plate current increases linearly as grid voltage increases until the characteristics reach saturation. The plate current then remains almost constant. When the grid voltage reaches its positive peak, the plate current begins to decrease linearly until the grid voltage again reaches cut-off. It remains zero and then starts over again. This procedure is illustrated in Figure 8. Without much error we can draw the waveform as Figure 9, where $e_b = E_{bb} - i_b R_L$.

Next, consider the circuit shown in Figure 10. Assume that L is an ideal inductance, that is without any losses. When the grid voltage is zero, the tube conducts, all the steady plate current goes through the inductance without voltage drop, plate voltage e_b is then equal to E_{bb}. When a large negative gate is applied to the grid, the tube cuts off. The plate current tends to change to zero from an initial steady value i_b. Because of the presence of the inductance, a negative voltage $L\frac{di}{dt}$ (negative with respect to the polarity in Figure 11.) is produced across the R-C-L circuit to prevent the change of current. The R-C-L circuit starts to oscillate. The oscillation is damped very rapidly by the resistance R. At the instant oscillations commence, the plate voltage e_b is equal to $E_{bb} - (-L\frac{di}{dt})$ which is almost two times of E_{bb}. By the same reason, when the tube conducts again we have another pulse only in this case the polarity is reversed. Therefore if we feed the grid with a rectangular wave, very narrow pulses, alternatively positive and negative, are produced.

Now, put these three circuits together and feed with a delay

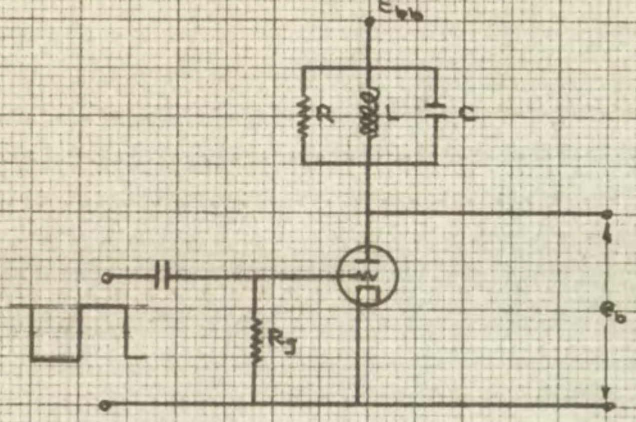


Fig. 10. Circuit Diagram

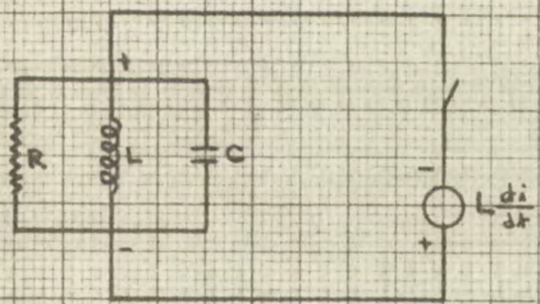


Fig. 11. Equivalent Circuit
For Oscillation

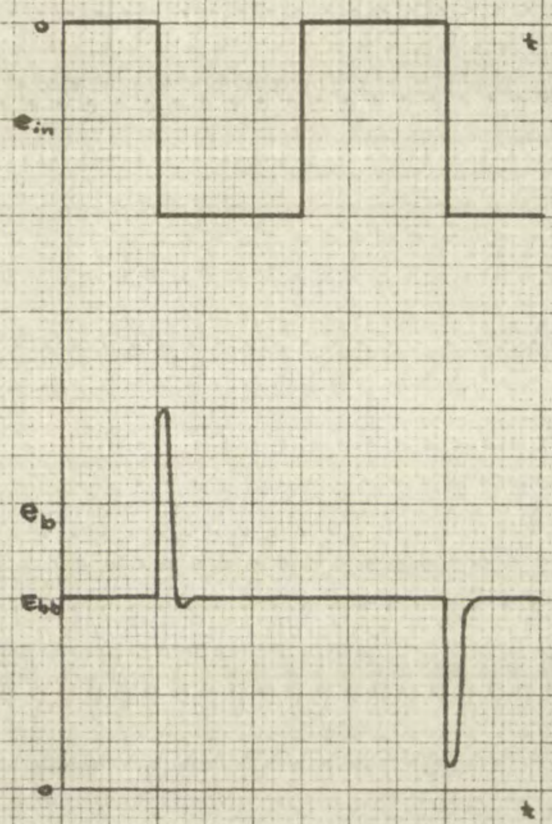


Fig. 12. Waveform for the Circuit shown in Fig 10.

pulse. A sequense of alternatively positive and negative narrow pulses is obtained. Through the first tube a number of sine wave cycles are obtained during the pulse duration. The second tube changes these sine waves into recatangular waves and the third tube changes rectangular waves into very narrow pulses. It should be emphasized that these narrow pulses only occur during the interval of the initiating pulse duration. If the input delay pulse is the same delay pulse used in the indicator circuit, these narrow pulses occur during the sweep. We can thus calibrate the indicator during the sweep poriod because the time interval between adjacent pulses is the same. In other words these narrow pulses divide the pulse duration into a number of equal subdivisions. By identifying the echo pulse with these narrow pulses the distance between the target and the transmitting station can be estimated. This process is called range marking. The circuit diagram and the waveforms are shown in Figures 13 and 14.

We have seen two applications of the delay circuit to the radar system. As one readily sees the delay circuit plays important role in both cases.

pulse. A sequence of [illegible] is obtained. Through the [illegible] of [illegible] obtained during the pulse length [illegible] waves into rectangular waves [illegible] waves into very narrow pulses. [illegible] narrow pulses only occur during the [illegible] of the [illegible] duration. If the [illegible] delay [illegible] indicator circuit, these narrow pulses [illegible] thus calibrate the indicator during the [illegible] interval between adjacent [illegible] in the [illegible] narrow pulses divide [illegible] divisions. By [illegible] distance between the target and the transmitting station [illegible] mated. This process is called range [illegible] waveforms are shown [illegible].

We have [illegible] system. As the [illegible] both [illegible].

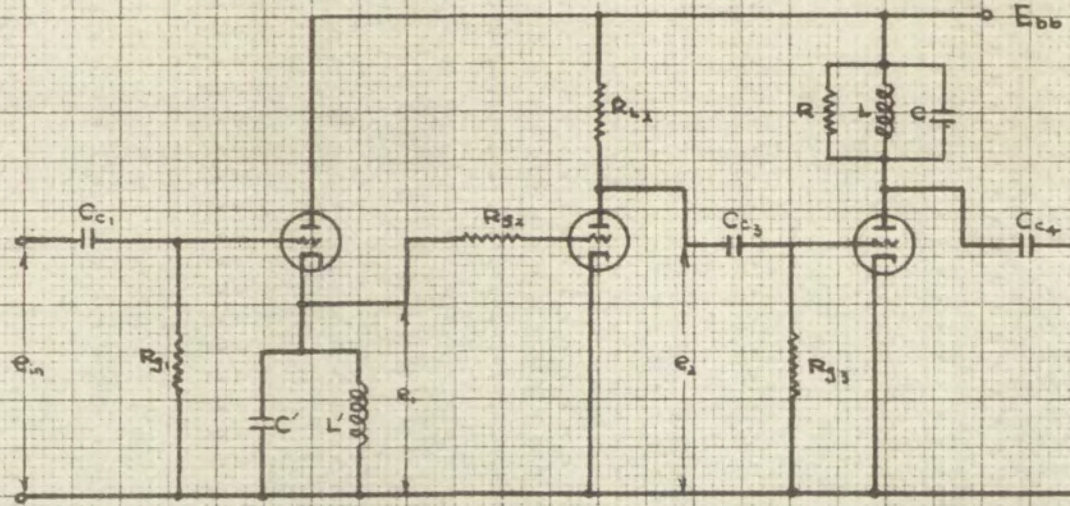


Fig. 13. Application of delay circuit to range marker.

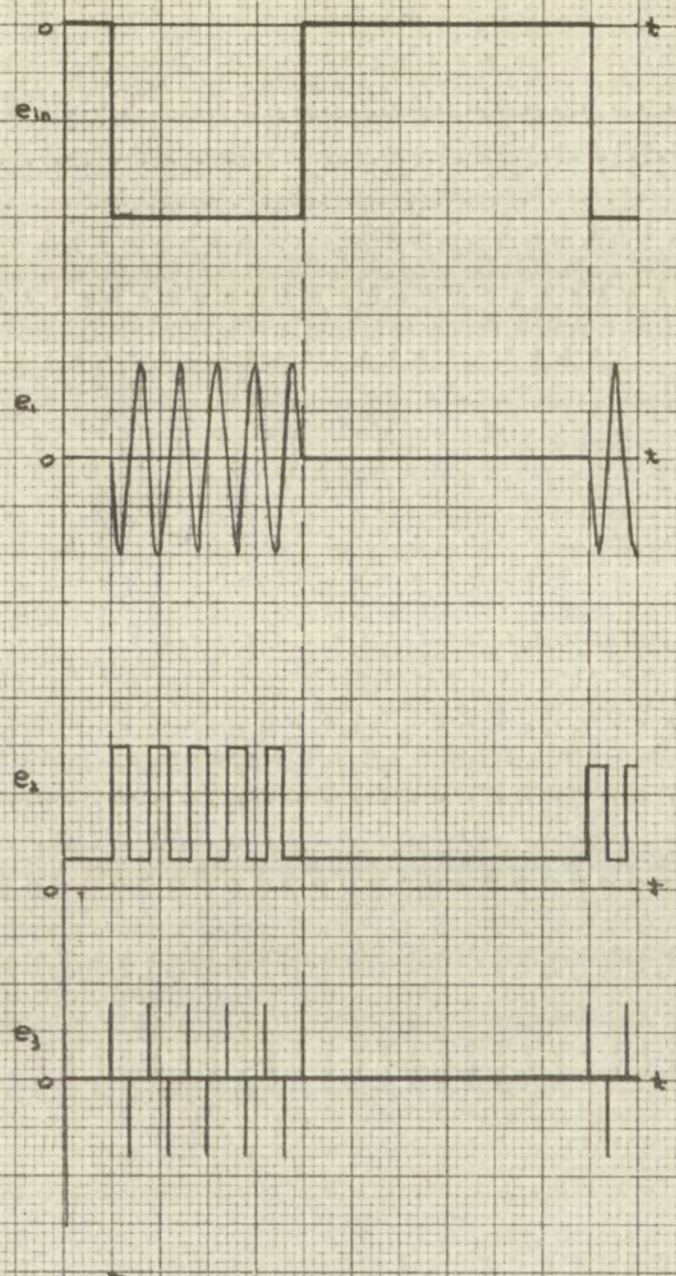


Fig. 14. Waveforms for Range Marker Circuit Shown in Fig 13.

3. Circuits Producing Delay Pulses

In this paragraph a few circuits which produce delay pulse will be examined. However, it is not to be implied that these are the only ones. In fact, there are numbers of circuits which will produce delay pulses.

A. Pentode Trigger Circuit

Consider the pentode trigger circuit as shown in Figure 15. The circuit function is due to the fact that the negative suppressor grid prevents all of the electrons from reaching the plate and forces some of them to return to the screen grid. The circuit can be triggered by changing the voltage between any two electrodes or by varying the value of the circuit parameter. It can also be triggered by introducing a controlled voltage between any two electrodes. For the simplicity of our discussion it is to be triggered by inserting a controlled voltage into the suppressor grid. During the process of triggering a rectangular pulse is produced across the plate resistor. Suppose the suppressor voltage is zero at first and the tube is conducting. The plate current is then constant and so is the voltage across the plate resistor. Now if a negative voltage is inserted in series with the suppressor grid, triggering starts and continues until the plate current cuts off, the voltage across the plate resistor is then zero. Next a positive voltage is inserted into the suppressor grid and the circuit restores its original condition. The voltage across the plate resistor changes

3. Circuits Producing Delay Pulses

In this paragraph, the circuits which [illegible] will be examined. However, it is not to be [illegible] ones. In fact, there are a number of circuits which [illegible] pulses.

4. Pentode Trigger Circuit

Consider the pentode trigger circuit as shown in Figure 17. The circuit functioning is due to the fact that the negative suppressor grid prevents all of the electrons from reaching the plate and causes some of them to return to the screen grid. The circuit can be triggered by changing the voltage through the [illegible] or by varying the value of the circuit [illegible] by [illegible] a controlled voltage [illegible] the [illegible] of our discussion it is to be [illegible] by inserting a controlled voltage into the suppressor [illegible] rectangular pulse is produced [illegible]. Suppose the suppressor voltage is [illegible] the plate current is then cut off and [illegible] across the plate resistor, [illegible] if a negative voltage is [illegible] in series with the [illegible] triggering starts the [illegible] the plate [illegible] the voltage across the plate resistor [illegible] voltage is [illegible] its original [illegible] the voltage across the plate resistor [illegible]

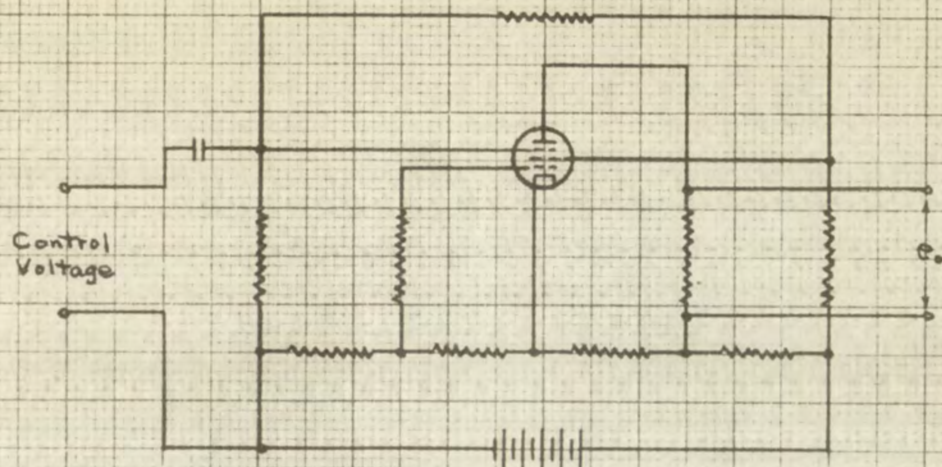


Fig. 15. Pentode Trigger Circuit

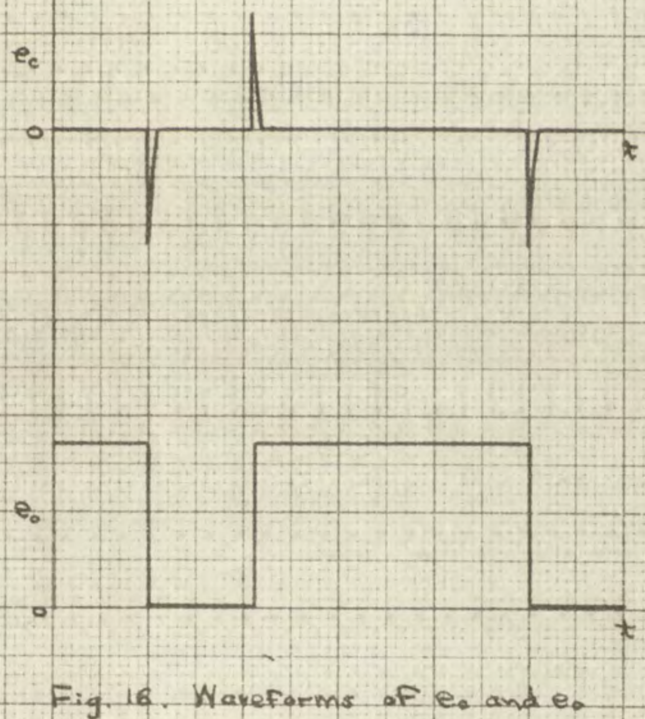


Fig. 16. Waveforms of e_c and e_o
For Pentode Trigger Circuit

from zero to its initial value accordingly. It is readily seen that by adjusting the time interval between two triggering voltages we can change the pulse duration. The waveform is illustrated in Figure 16.

B. Eccles-Jordan Trigger Circuit

Consider the Eccles-Jordan trigger circuit as shown in Figure 17. The circuit functions because the current can flow through only on tube at a time. Suppose that both tubes conduct. A small increase of current in one tube increases the voltage drop in the corresponding coupling resistance, thus decreases the grid voltage of the other tube. The decrease of the grid voltage decreases the plate current of the second tube which in turn increases the grid voltage of the first tube and increases the plate current of the first tube accordingly. The process repeats until the second tube cuts off. When the tube conducts the voltage across the plate resistor is constant which is equal to the product of plate current i_b and plate resistor R_L. When the tube cuts off, the voltage across the plate resistor is zero. Thus a rectangular pulse is obtained. The circuit can again be triggered in many ways as in the case of pentode trigger circuit. If we introduce a negative voltage between any two electrodes to make one tube conduct, we can introduce a positive voltage between the same electrodes to make the other tube conduct. By changing the time interval between the two voltages we can change the pulse duration. The waveform is shown in Figure 18.

from zero to the initial [illegible] result [illegible] by adjusting the time interval between [illegible] frequency [illegible] change the pulse duration. [illegible]

2. Eccles-Jordan Trigger Circuit

Consider the Eccles-Jordan trigger circuit shown in Figure 17. The circuit function [illegible] the current [illegible] only one tube at a time. Suppose [illegible] of current in one tube increases the [illegible] the corresponding coupling resistance [illegible] of the other tube. The decrease of [illegible] decreases the [illegible] current of the second tube [illegible] first tube [illegible] accordingly. The [illegible] tube conducts the [illegible] is equal to [illegible] When the tube [illegible] off, [illegible] Thus a rectangular [illegible] in many ways as in the [illegible] duce a negative voltage [illegible] conduct, we [illegible] to make the other tube conduct [illegible] the two voltages we can change the pulse duration [illegible] shown in Figure 18.

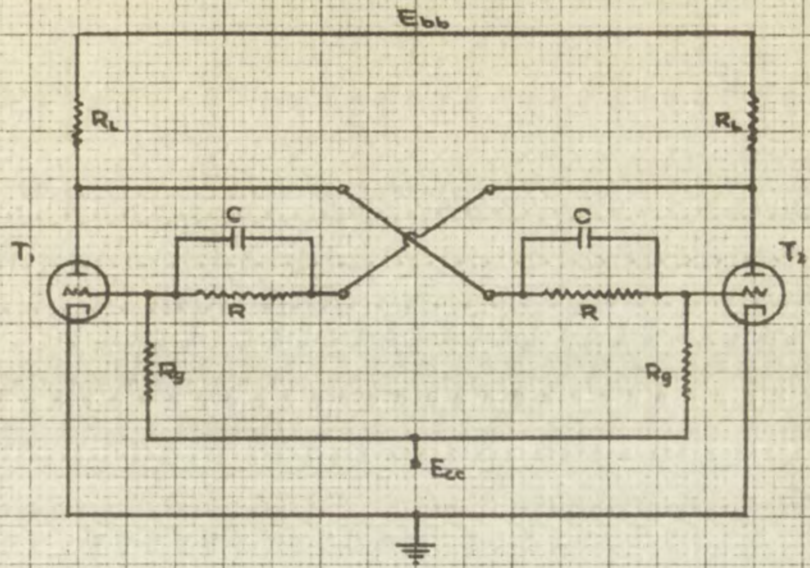


Fig. 17. Eccles-Jordan Trigger Circuit

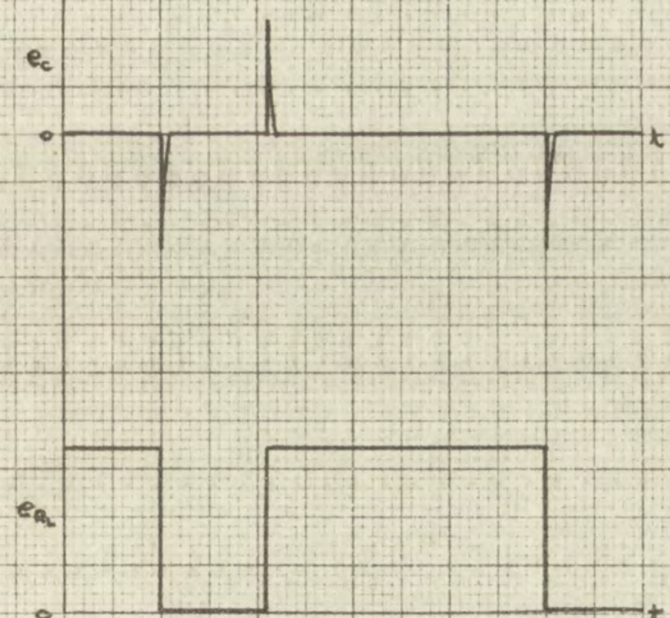


Fig. 18. Waveform for Eccles-Jordan Trigger Circuit

C. Multivibrator

If, in the Eccles-Jordan trigger circuit, we change the DC coupling into AC coupling and make the capacitance of the condensers larger, the circuit is called multivibrator. The circuit is shown in Figure 19. At the instant the power supply is turned on, bias on each tube is zero and there is no initial charge on the condenser. Thus both tubes start conducting and both condensers start accumulating charge. Now if an increase in current occurs through one of tubes, say T-2, the plate voltage e_{b2} drops, since $e_{b2} = E_{bb} - i_{b2}R_{L2}$. The drop of e_{b2} causes the plate current of T-1, i_{b1}, to drop. The plate voltage of T-1, e_{b1}, which is equal to $E_{bb} - i_{b1}R_{L1}$, increases. The increase of e_{b1} increases e_{g2}, and thus increases i_{b2} further more. The process continues until T-1 cuts off. Now the charge previously accumulated on C_1 leaks through R_{g1} and increases e_{g1}. As e_{g1} increases to the value of cut-off of the tube, T-1 conducts with a tendency of increasing the plate current because e_{g1} is still increasing. This is exactly the same situation as when the plate current of T-2 is increasing. Therefore i_{b2} increases until T-1 cuts off. Then the process repeats again. During the process a rectangular pulse is obtained across the tube.

This circuit is different from the precious two. First, it does not need an external triggering agent, or it is said to be self trigger. Second, the frequency is determined by the circuit parameters,

C. Multivibrator [illegible]

If, in the [illegible] coupling, [illegible] coupling into CE coupling, and [illegible] larger, the circuit is called [illegible]. [illegible] is shown in Figure 19. At the instant [illegible] the power supply [illegible] tube is zero and [illegible] the initial [illegible] tubes start conducting [illegible]. Now if an increase in current [illegible] the plate voltage e_{b2} drops [illegible] causes the plate current of T-1, i_{b1} [illegible] T-1, e_{b1}, which [illegible]. [illegible] e_{b1} increases e_{c2} and [illegible] continues until T-1 [illegible] on C, leaks through R_g [illegible] value of cut-off of the tube [illegible] ing the plate current [illegible] the same [illegible] the plate current of [illegible]. Therefore e_{b2} increases until [illegible] again. During the [illegible] tube.

This circuit [illegible] does not need an external trigger [illegible] trigger. Second, the frequency is determined by [illegible]

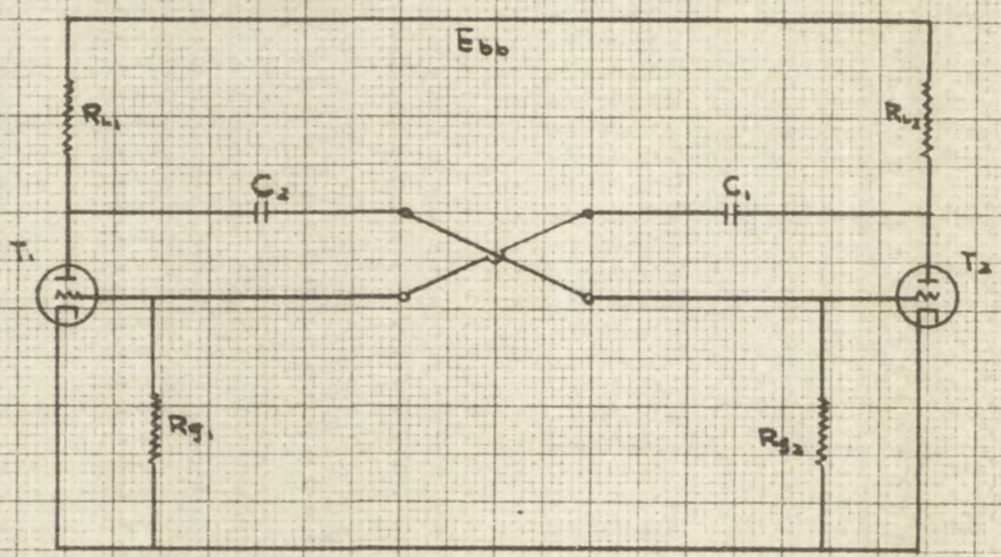


Fig. 19. Free Running Multivibrator

not by external circuit. By changing the circuit parameters the frequency can be changed.

However, the frequency can be controlled by introducing a trigger pulse into the cothode. This is called synchronization. We can also return one of the grid to a positive terminal. By varying the value of the positive voltage the pulse duration can be varied.

D. Cathode-coupled Multivibrator and Phantastron

Several circuits which produce rectangular pulses have been briefly discussed. In the case of the Multivibrator the waveform is produced without external stimulus. In the case of the pentode trigger circuit or the Eccles-Jordan trigger circuit, an external signal was required to start the pulse and another signal to end the pulse. It is natural to conclude that it may be possible for a rectangular pulse to started by an external signal and to be ended by itself. The cathode-coupled multivibrator and phantastron are the examples for the last case. Thus, it is possible to divide the circuits that produce rectangular pulses into three categories:

1. Those in which the waveform is produced without external stimulus. Such circuits are called "free wheeling" or free running circuits.

2. Those in which one of the wavefronts is induced externally. Such circuits are called single stroke, flip-flop, or start-stop circuits.

3. Those in which both of the wavefronts are induced externally. Such circuits are called flopover, lockover, or scale-of-two circuits.

Moreover, it was noted that in the case of the pentode trigger circuit or the Eccles-Jordan trigger circuit that the pulse duration

B. Cathode-coupled Multivibrators and Free-running [illegible]

Several circuits which produce rectangular pulses have been briefly discussed. In the case of the [illegible] [illegible] [illegible] produced without external stimulus. In the case [illegible] circuit or the Eccles-Jordan trigger circuit, [illegible] was required to start the pulse and [illegible] It is natural to conclude that [illegible] pulse be started by an external signal and [illegible] cathode-coupled multivibrator [illegible] the last case. Thus, it is [illegible] to divide the circuits that produce rectangular pulses into three categories:

1. Those in which the waveform is produced without external stimulus. Such circuits are called "free-running" or free-running circuits.

2. Those in which one of the [illegible] [illegible] [illegible]. Such circuits are called single-[illegible], or start-stop circuits.

3. Those in which both of the [illegible] [illegible] [illegible]. Such circuits are called flip-flops, [illegible], or [illegible] circuits.

Moreover, it was [illegible] that in the case of the [illegible] [illegible] circuits of the Eccles-Jordan [illegible] [illegible] [illegible]

could be changed by varying the time interval between the two triggering signals applied. However, this is not very practical since such signals are not easily controlled. In a multivibrator, if one of the grids is returned to a positive potential, the pulse duration can be varied by changing this potential. However, the frequency is changed at the same time.

In the cathode-coupled multivibrator and the phantastron, the triggering signal is easily applied because it consists of only one impulse for each cycle of the controlled circuit. A pulse is a satisfactory waveform. Moreover, an essential property of these two circuits is that the pulse duration is almost linearly proportional to certain quantities in the circuit, which in turn are linearly proportional to the value of certain circuit parameters. Thus by changing the value of a circuit parameter the pulse duration can be changed very easily. Hence, a linear relation between the value of the circuit parameter and the pulse duration will exist.

This property is extremely important. As we have seen in the application of the delay circuit to the range marker, the sharp pulses divide the pulse duration into a number of equal-spaced subdivisions. If we change the pulse duration, the space between two sharp pulses, or the time delay between two sharp pulses, changes accordingly. Since there is a linear relation between the subdivision and the pulse duration, or between the subdivision and the value of the circuit parameter, we can thus read the time delay from the corresponding value

of the circuit parameter by proper calibration. For the asme reason, we can linearly adjust the time interval during the saw-tooth sweep by adjusting the value of the circuit parameter.

of the circuit parameter by proper calibration. For the same reason, we can linearly adjust the time interval during the saw-tooth sweep by adjusting the value of the circuit parameter.

II. CATHODE-COUPLED MULTIVIBRATOR

1. Introduction

The most important property of the cathode-coupled multivibrator is that the pulse duration is almost linearly proportional to the bias voltage of tube 1. The two cathodes are coupled through a common resistor. The plate-grid coupling is used in one direction only instead of two as in the case of ordinary plate coupled multivibrator. Under normal conditions, tube 2 is conducting because the grid voltage of tube 2 is positive. The static plate current produces a voltage across the cathode resistor which is sufficient to overcome the bias voltage of tube 1 and make it cut off. When a positive trigger pulse is applied to the grid of tube 1, tube 1 conducts. The drop in plate voltage of tube 1 causes the grid voltage of tube 2 to drop by the same amount because of the presence of the condenser, thus cutting tube 2 off. Now, the condenser starts to charge, and the grid voltage of tube 2 starts to increase again until cut off is reached. Tube 2 conducts and the process starts over again.

2. Circuit and Nomenclature

The circuit diagram is shown in Figure 21. Let

E_{bb} = Plate supply voltage

e_{bn1} = Voltage from plate 1 to ground

e_{bn2} = Voltage from plate 2 to ground

e_{b1} = Voltage from plate 1 to cathode

II. CATHODE-COUPLED MULTIVIBRATOR

1. Introduction

The most important property of the cathode-coupled multivibrator is that the pulse duration is fixed [illegible] by the grid voltage of tube 1. The two cathodes are tied [illegible] through a common resistor. The plate-grid coupling is used in one direction only instead of two as in the case of ordinary plate-coupled multivibrator. Under normal conditions, tube 2 is conducting because its grid voltage is [illegible] positive. The static plate current produces a voltage across the cathode resistor which is sufficient to [illegible] the grid voltage of tube 1 and make it cut off. When a positive trigger pulse is applied to the grid of tube 1, tube 1 conducts. The drop in plate voltage of tube 1 causes the grid voltage of tube 2 to drop by the same amount because of the presence of the condenser, thus cutting tube 2 off. Then the condenser starts to charge, and the grid voltage of tube 2 starts to rise again until cut off is reached. Then 2 conducts and the process starts over again.

2. Circuit and Nomenclature

The circuit diagram is shown in Figure 2.1. [illegible]

E_{bb} = Plate supply voltage

e_{bn1} = Voltage from plate 1 to ground

e_{bn2} = Voltage from plate 2 to ground

e_{b1} = Voltage from plate 1 to cathode

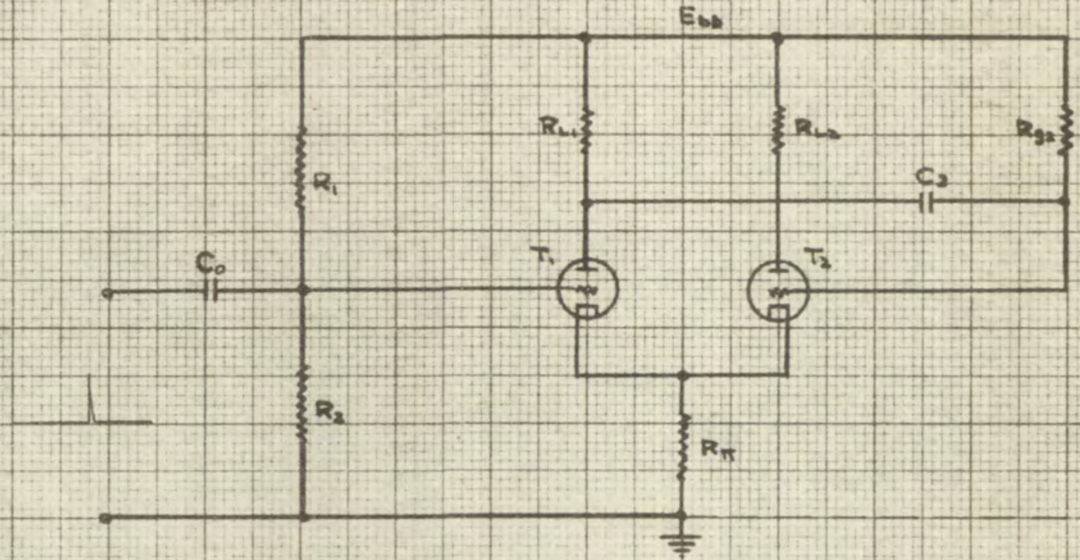


Fig. 21. Cathode-coupled Multivibrator

e_{b2} = Voltage from plate 2 to cathode

e_{cn1} = Voltage from grid 1 to ground

e_{cn2} = Voltage from grid 2 to ground

e_{c1} = Voltage from grid 1 to cathode

e_{c2} = Voltage from grid 2 to cathode

e_{k} = Voltage from cathode to ground

$\bar{r}_p$ = Static plate resistance

μ = Amplification factor

e_{co1} = Cut-off voltage when tube 1 cuts off

e_{co2} = Cut-off voltage when tube 2 cuts off

i_{b1} = Plate current of tube 1

i_{b2} = Plate current of tube 2

3. Mathematical Analysis

Analysis proceeds as follows:

A. Condition I - tube 2 conducting and tube 1 cut off

Under this condition the circuit is equivalent to the one shown in Figure 22.

(1) Grid 2, being returned to E_{bb} through a resistor R_{g2}, is maintained positive; it draws current. But since R_{g2} is very large, all the voltage drops in R_{g2}. Therefore the voltage between grid 2 and cathode is practically zero. In other words tube 2 is biased at very nearly zero voltage.

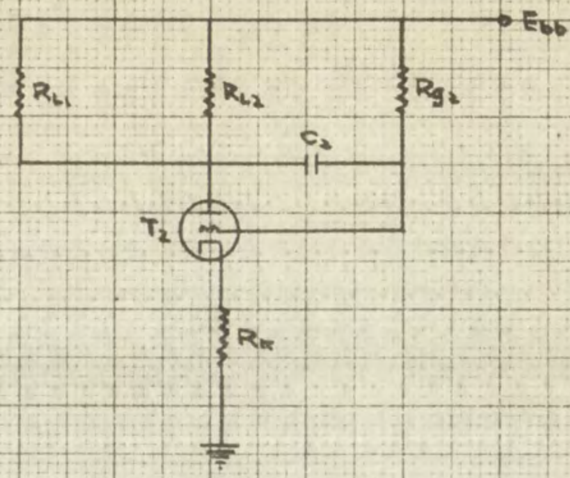


Fig. 22. When T-2 Conducts

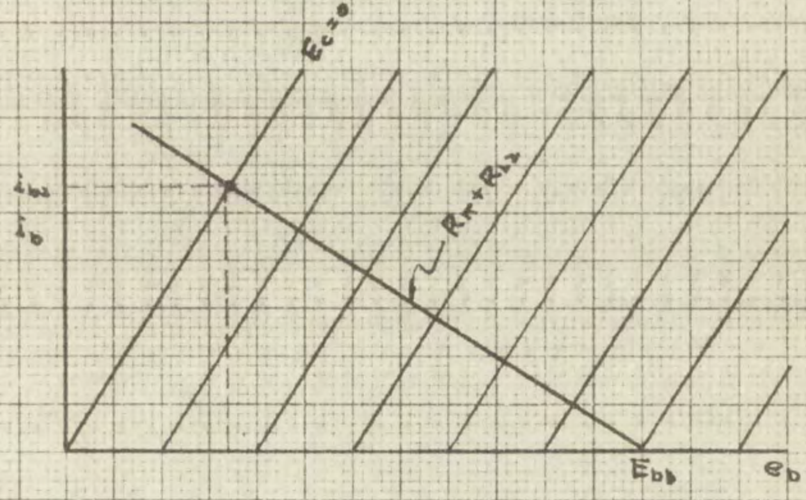


Fig 23. Plate Characteristic

(2) The plate current 2 can thus be determined from the static plate characteristics as shown in Figure 23.

$$i_{b2} = \frac{E_{bb}}{R_{L2} + R_{\pi} + \bar{r}_p}$$

(3) Since $e_{c1} = e_{cn1} - i_{b2} R_{\pi}$, to insure that tube 1 cuts off, the greatest value of e_{cn1} is fixed. Or we say that the greatest value of e_{cn1} is determined by R_{π} and R_{L2}.

The cut-off voltage e_{co1} for tube 1 can be determined as follows. From the plate voltage-grid voltage characteristic (Figure 24) we know that

$$\frac{\partial e_b}{\partial e_c} = \mu$$

If we assume that the plate characteristics (Figure 25) are equally spaced, then we can find e_{co1} by

$$e_{co1} = -\frac{1}{\mu} e_{b1}$$

Now,

$$e_{b1} = E_{bb} - i_{b2} R_{\pi}$$

$$e_{co1} = -\frac{1}{\mu} e_{b1}$$

$$e_{c1} = e_{cn1} - i_{b2} R_{\pi}$$

Condition for cut-off

$$e_{c1} < e_{co1}$$

$$e_{cn1} - \frac{E_{bb}}{R_{L2} + R_{\pi} + \bar{r}_p} R_{\pi} < -\frac{1}{\mu} \left(E_{bb} - \frac{E_{bb}}{R_{L2} + R_{\pi} + \bar{r}_p} R_{\pi} \right)$$

$$e_{cn1} < -\frac{1}{\mu} E_{bb} + \left(1 + \frac{1}{\mu}\right) \left(\frac{E_{bb} R_{\pi}}{R_{L2} + R_{\pi} + \bar{r}_p} \right)$$

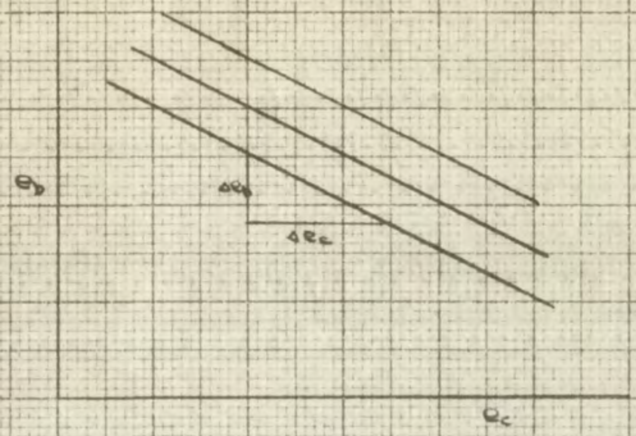


Fig 24. Plate Voltage - Grid Voltage Characteristic.

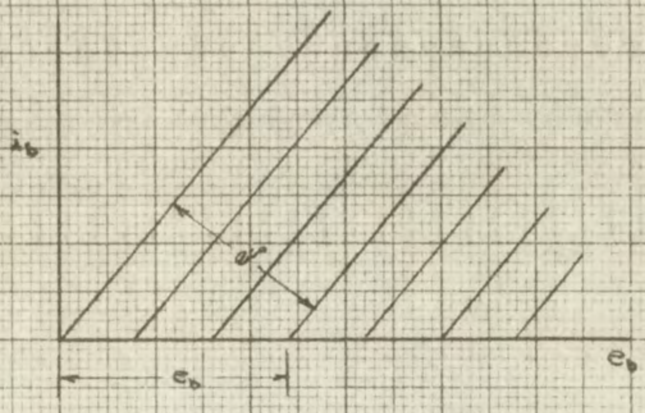


Fig. 25. Plate Characteristic.

B. Condition 2 - When the trigger pulse is applied

When the trigger pulse is applied, tube 1 conducts suddenly and tube 2 cuts off at the same time. We can then redraw the circuit as in Figure 26.

(1) First, assume that tube 2 cuts off at the instant tube 1 conducts. Later we will check to see if this is true.

Since e_{cn1} remains constant, e_{c1} must satisfy the condition:

$$e_{cn1} = e_{c1} + e_{k}$$

From the plate characteristics (Figure 27), we have

$$e_{cn1} = e_{c1} + e_{k} , \quad \text{or} \quad e_{cn1} = e_{c1} + i_{b1} R_{k}$$

$$\frac{E_{bb} - e_{b1}}{R_{L1}} = i_{b1} , \quad E_{bb} - e_{b1} = i_{b1} R_{L1}$$

$$\frac{e_{b1} + \mu e_{c1}}{\bar{r}_p} = i_{b1} , \quad e_{b1} + \mu e_{c1} = i_{b1} \bar{r}_p$$

$$E_{bb} - i_{b1} R_{L1} = i_{b1} \bar{r}_p - \mu e_{c1}$$

$$i_{b1} (R_{L1} + \bar{r}_p) = E_{bb} + \mu e_{c1}$$

$$i_{b1} = \frac{E_{bb} + \mu e_{c1}}{R_{L1} + \bar{r}_p} = \frac{E_{bb} + \mu (e_{cn1} - i_{b1} R_{k})}{R_{L1} + \bar{r}_p}$$

$$i_{b1} \left(1 + \frac{\mu R_{k}}{R_{L1} + \bar{r}_p}\right) = \frac{E_{bb} + \mu e_{cn1}}{R_{L1} + \bar{r}_p}$$

$$\therefore \quad i_{b1} = \frac{E_{bb} + \mu e_{cn1}}{R_{L1} + \bar{r}_p + \mu R_{k}}$$

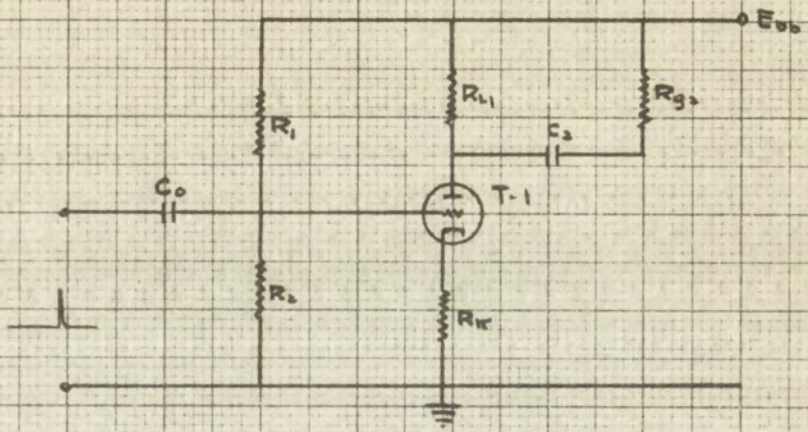


Fig. 26. When Tube 1 Conducts.

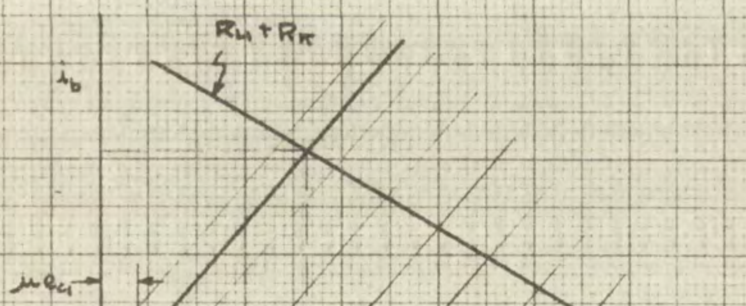


Fig. 27. Plate Characteristic

$$e_{bn1} = E_{bb} - i_{b1} R_{L1} = E_{bb} - \frac{E_{bb} + \mu e_{cn1}}{R_{L1} + r_p + \mu R_K} R_{L1}$$

(2) Now check to see whether or not tube 2 cuts off. Since there is a condenser between plate 1 and grid 2, the drop in e_{bn1} causes e_{cn2} to drop by the same amount.

Before tube 1 conducts, $e_{bn1} = E_{bb}$; and after tube 1 conducts, $e_{bn1} = e_{bn1}$. Therefore the drop is

$$E_{bb} - e_{bn1}$$

$$\therefore \quad e'_{cn2} = e_{cn2} - (E_{bb} - e_{bn1}) = i_{b2} R_K - (E_{bb} - e_{bn1})$$

$$e'_{c2} = e'_{cn2} - e'_K = e'_{cn2} - i_{b1} R_K$$

$$e'_{co2} = -\frac{1}{\mu} e'_{b2} = -\frac{1}{\mu}(E_{bb} - e'_K) = -\frac{1}{\mu}(E_{bb} - i_{b1} R_K)$$

The condition for tube 2 to cut off is

$$e'_{c2} < e'_{co2}$$

Here, the quantities in the expressions for e'_{c2} and e'_{co2} are all known; therefore we are able to get another limitation on e_{cn1}.

C. After tube 2 is cut off, the condenser C_2 starts to charge. The circuit in which the charging process takes place is shown in Figure 28. As far as the transient current is concerned the circuit can be redrawn as in Figure 29. Since

$$R_{g2} \gg \frac{1}{\frac{1}{R_{L1}} + \frac{1}{r_p}}$$

(2) Now each [illegible] [illegible] [illegible] [illegible]. [illegible] there is a condenser between [illegible] [illegible] the [illegible] to drop by the same amount.

Before tube 1 [illegible] [illegible] [illegible]

[illegible]. Therefore the [illegible]

[illegible]

[illegible]

[illegible]

[illegible]

The condition for tube 2 to [illegible] is

[illegible]

Here, the quantities in the parenthesis [illegible] and [illegible] are all [illegible]; therefore we are able to [illegible] another [illegible] [illegible].

C. After tube 3 is cut off, the [illegible] [illegible] [illegible]. The circuit in which the charging process takes place is shown in Figure 23. As far as the [illegible] current is concerned the circuit can be redrawn as in Figure 24, where

[illegible]

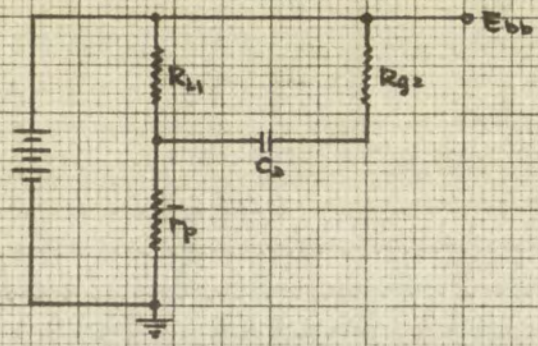


Fig. 28. Charging Circuit.

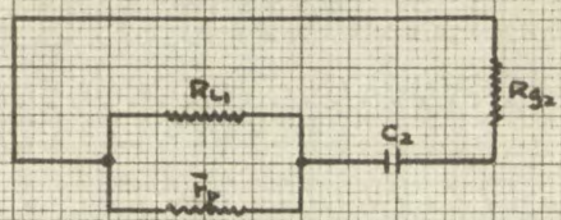


Fig. 29. Charging Circuit

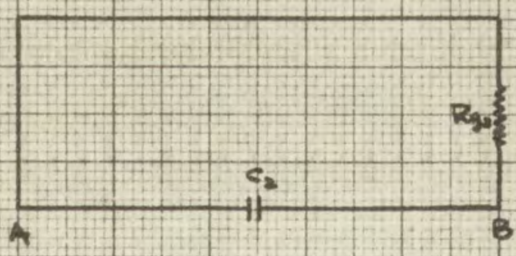


Fig. 30. Charging Circuit.

the circuit becomes as indicated in Figure 30. At one end (A) of C_2 the voltage is E_{bb}; at the other end (B) is e'_{cn2}. When the voltage at B reaches $e_{co2} + e_{\kappa}$, tube 2 conducts again. The time constant of the circuit is then $C_2 R_{g2}$.

4. Calculation of the Pulse Duration

From the above analysis we see that the pulse duration depends primarily upon the following three quantities:

(1) Cut-off voltage of tube 2 when tube 1 is conducting.

(2) The initial value of e_{cn2} when tube 1 conducts suddenly, namely e'_{cn2}.

(3) The time constant of the charging circuit.

These factors will be examined separately.

A. Cut-off voltage of tube 2 when tube 1 is conducting

The cut-off voltage depends on plate voltage

$$e_{co2} = \frac{1}{\mu} e_{b2}$$

now,

$$e_{b2} = E_{bb} - i_{b1} R_{\kappa}$$

It was previously shown that

$$i_{b1} = \frac{E_{bb} + \mu e_{on1}}{R_{L1} + r_p + \mu R_{\kappa}}$$

$$\therefore \quad e_{b2} = E_{bb} - R_K \frac{E_{bb} + \mu e_{cn1}}{R_{L1} + \bar{r}_p + \mu R_K}$$

$$\therefore \quad e_{co2} = \frac{1}{\mu}\left[E_{bb}\left(1 - \frac{R_K}{R_{L1} + \bar{r}_p + \mu R_K}\right) - \frac{\mu e_{cn1} R_K}{R_{L1} + \bar{r}_p + \mu R_K}\right]$$

B. The initial value of e_{cn2}, namely e_{cn2}',

$$e_{cn2}' = e_{cn2} - \text{Voltage Drop of Tube 1}.$$

Before tube 1 conducts

$$e_{cn2} = i_{b2} R_K = R_K \frac{E_{bb}}{R_{L2} + \bar{r}_p + R_K}$$

Voltage drop of tube 1 $= E_{bb} - (E_{bb} - i_{b1} R_{L1}) = i_{b1} R_{L1}$

$$i_{b1} R_{L1} = R_{L1} \frac{E_{bb} + \mu e_{cn1}}{R_{L1} + \bar{r}_p + \mu R_K}$$

$$\therefore \quad e_{cn2}' = \frac{R_K E_{bb}}{R_{L2} + \bar{r}_p + R_K} - \frac{R_{L1}(E_{bb} + \mu e_{cn1})}{R_{L1} + \bar{r}_p + \mu R_K}$$

C. Time constant of the charging circuit

It was shown that

$$\text{Time Constant} = C_2 R_{g2}$$

Now, at the time the circuit starts charging, the voltage difference between the two plates of the condenser is

$$E_{bb} - e_{cn2}'$$

At the instant tube 2 conducts again, the voltage difference is

$$E_{bb} - (e_{co2} + e_K) = E_{bb} - (e_{co2} + i_{b1} R_K)$$

We can thus calculate the pulse duration t as follows:

$$E_{bb} - (e_{co2} + e_K) = (E_{bb} - e_{cn2}')\, e^{-\frac{t}{C_2 R_{g2}}}$$

$$E_{bb} - (e_{co2} + e_K) = E_{bb} - \frac{1}{\mu}\left[E_{bb}\left(1 - \frac{R_K}{R_{L1} + \bar{r}_p + \mu R_K}\right) - \frac{\mu e_{cn1} R_K}{R_{L1} + \bar{r}_p + \mu R_K}\right] - \frac{E_{bb} + \mu e_{cn1}}{R_{L1} + \bar{r}_p + \mu R_K} R_K$$

$$= E_{bb} - \frac{1}{\mu} E_{bb} + \frac{1}{\mu}\frac{E_{bb} R_K}{R_{L1} + \bar{r}_p + \mu R_K} + \frac{1}{\mu}\frac{\mu e_{cn1} R_K}{R_{L1} + \bar{r}_p + \mu R_K}$$

$$- \frac{E_{bb} R_K}{R_{L1} + \bar{r}_p + \mu R_K} - \frac{\mu e_{cn1} R_K}{R_{L1} + \bar{r}_p + \mu R_K}$$

$$= \left(1 - \frac{1}{\mu}\right)\left(E_{bb} - \frac{E_{bb} R_K + \mu e_{cn1} R_K}{R_{L1} + \bar{r}_p + \mu R_K}\right)$$

$$E_{bb} - e_{cn2}' = E_{bb} - \frac{R_K E_{bb}}{R_{L2} + \bar{r}_p + R_K} + \frac{R_{L1}(E_{bb} + \mu e_{cn1})}{R_{L1} + \bar{r}_p + \mu R_K}$$

$$= \frac{E_{bb}(R_{L2} + R_K + \bar{r}_p)(R_{L1} + \bar{r}_p + \mu R_K) - R_K E_{bb}(R_{L1} + \bar{r}_p + \mu R_K) + R_{L1}(E_{bb} + \mu e_{cn1})(R_{L2} + \bar{r}_p + R_K)}{(R_{L2} + \bar{r}_p + R_K)(R_{L1} + \bar{r}_p + \mu R_K)}$$

$$= \frac{E_{bb}(R_{L1} + \bar{r}_p + \mu R_K)(R_{L2} + \bar{r}_p) + R_{L1} E_{bb}(R_{L2} + \bar{r}_p + R_K) + \mu e_{cn1} R_{L1}(R_{L2} + \bar{r}_p + R_K)}{(R_{L2} + \bar{r}_p + R_K)(R_{L1} + \bar{r}_p + \mu R_K)}$$

$$= \frac{E_{bb}(R_{L2} + \bar{r}_p)(2R_{L1} + \bar{r}_p + \mu R_K) + R_{L1} R_K E_{bb} + \mu e_{cn1} R_{L1}(R_{L2} + \bar{r}_p + R_K)}{(R_{L2} + \bar{r}_p + R_K)(R_{L1} + \bar{r}_p + \mu R_K)}$$

$$\therefore \left(1 - \frac{1}{\mu}\right)\left(E_{bb} - \frac{E_{bb} R_K + \mu e_{cn1} R_K}{R_{L1} + \bar{r}_p + \mu R_K}\right)$$

$$= \frac{E_{bb}(R_{L2} + \bar{r}_p)(2R_{L1} + \bar{r}_p + \mu R_K) + R_{L1} R_K E_{bb} + \mu e_{cn1} R_{L1}(R_{L2} + \bar{r}_p + R_K)}{(R_{L2} + \bar{r}_p + R_K)(R_{L1} + \bar{r}_p + \mu R_K)}\, e^{-\frac{t}{C_2 R_{g2}}}$$

$$t = C_2 R_{g_2} \ln \frac{\dfrac{E_{bb}(R_{L2}+\bar{r}_p)(2R_{L1}+\bar{r}_p+\mu R_\pi)+R_{L1}R_\pi E_{bb}+\mu e_{cn1}R_{L1}(R_{L2}+\bar{r}_p+R_\pi)}{(R_{L2}+\bar{r}_p+R_\pi)(R_{L1}+\bar{r}_p+\mu R_\pi)}}{(1-\frac{1}{\mu})\left(E_{bb}-\dfrac{E_{bb}R_\pi+\mu e_{cn1}R_\pi}{R_{L1}+\bar{r}_p+\mu R_\pi}\right)}$$

$$= C_2 R_{g_2} \ln \frac{E_{bb}(R_{L2}+\bar{r}_p)(2R_{L1}+\bar{r}_p+\mu R_\pi)+R_{L1}R_\pi E_{bb}+\mu e_{cn1}R_{L1}(R_{L2}+\bar{r}_p+R_\pi)}{(1-\frac{1}{\mu})\left[E_{bb}(R_{L1}+\bar{r}_p+\mu R_\pi-R_\pi)-\mu e_{cn1}R_\pi\right](R_{L2}+\bar{r}_p+R_\pi)}$$

5. The Actual Values of the Circuit Parameters With Which Our Experimental Data Is Obtained

The tube used in our experiment is 6SN7. The values of the circuit parameters are as follows:

$R_{L1} = 20K$

$R_{L2} = 10K$

$R_\pi = 10K$

$R_{g2} = 2$ Meg

$E_{bb} = 250v$

$\mu = 20$

$r_p = 7700$ ohms

$R_1 = 0\text{-}1$ Meg

$R_2 = 100K$

$C_2 = 100\ \mu\mu F$

$C_0 = 20\ \mu\mu f$

6. Simplification of the analytic result

With the above values we can simplify our result as follows:

$\mu = 20$, $\frac{1}{\mu} \ll 1$.

$r_p = 7700\,\Omega$, $\bar{r}_p \doteq 10k$

$\frac{1}{2} R_{L1} = R_{L2} = R_K = \bar{r}_p = R$.

$$\therefore\ t = C_2 R_{g2} \ln \frac{E_{bb}(R_{L2}+\bar{r}_p)(R_{L1}+\bar{r}_p+\mu R_K) + R_{L1} R_K E_{bb} + \mu e_{cn1} R_{L1}(R_{L2}+\bar{r}_p+R_K)}{(1-\frac{1}{\mu})(R_{L2}+\bar{r}_p+R_K)\left[E_{bb}(R_{L1}+\bar{r}_p+\mu R_K - R_K) - \mu e_{cn1} R_K\right]}$$

$$= C_2 R_{g2} \ln \frac{E_{bb}\left[2R(\mu+5)R + 2R^2\right] + e_{cn1}\left[2R\mu(3R)\right]}{E_{bb}\left[3R(\mu+2)R\right] - e_{cn1}\left[3R^2\mu\right]}$$

$$= C_2 R_{g2} \ln \frac{R^2\left[E_{bb} \cdot 2(\mu+6) + 6\mu e_{cn1}\right]}{R^2\left[E_{bb} \cdot 3(\mu+2) - 3\mu e_{cn1}\right]}$$

$$= C_2 R_{g2} \ln \frac{2(\mu+6)E_{bb} + 6\mu e_{cn1}}{3(\mu+2)E_{bb} - 3\mu e_{cn1}}$$

$$= C_2 R_{g2} \ln \frac{1 + \frac{3\mu}{\mu+6}\frac{e_{cn1}}{E_{bb}}}{\frac{3}{2}\frac{\mu+2}{\mu+6} - \frac{3}{2}\frac{\mu}{\mu+6}\frac{e_{cn1}}{E_{bb}}}$$

$$= C_2 R_{g2} \ln \frac{1 + 3\frac{e_{cn1}}{E_{bb}}}{\frac{3}{2} - \frac{3}{2}\frac{e_{cn1}}{E_{bb}}}$$

$$= C_2 R_{g2} \ln \frac{\frac{2}{3} + \frac{2e_{cn1}}{E_{bb}}}{1 - \frac{e_{cn1}}{E_{bb}}}$$

7. Experimental Data and Result

The following data is obtained from our experiment with the circuit constants specified in Paragraph 5.

A. With frequency and time constant fixed. Frequency = 10,000 cycles per second; R_{g2}=2 Meg.

(1) R_K = 10 K

e_{cn1} (volt)	Pulse Duration (μsec)
48	30.0
50	35.0
55	45.0
60	55.0
65	62.5
70	67.5

(2) $R_K = 15K$

e_{cn1} (volt)	Pulse Duration (μ sec)
71	32.5
75	40.0
80	50.0
85	62.5
90	72.5
95	77.5

(3) $R_K = 20K$

e_{cn1} (volt)	Pulse Duration (μ sec)
90	30.0
95	42.5
100	52.5
105	62.5
110	70.5

(4) $R_K = 7.5$ K

e_{cn1} (volt)	Pulse Duration (μ sec)
30	27.5
35	35.0
40	50.0
45	62.5
50	75.0
54	80.0

B. With frequency and R_K fixed. Frequency = 10,000 cycles per second; R_K = 10K

(1) $R_{g2} = 2.5$ Meg.

e_{cn1} (volt)	Pulse Duration (μ sec)
46	30.0
50	42.5
55	55.0
60	72.0
64	80.0

(2) $R_{g2} = 3$ meg.

e_{cn1} (volt)	Pulse Duration (μ sec)
46	32.5
50	45.0
55	65.0
60	80.0

(3) $R_{g2} = 3.5$ meg

e_{cn1} (volt)	Pulse Duration (μ sec)
46	40.0
50	55.0
55	72.5
56	77.5

C. Frequency = 10,000 cycles per second; R_K = 20K; and R_{g2} = 3.5 Meg.

e_{cm1} (volt)	Pulse Duration (μ sec)
77	35.0
80	45.0
82	50.0
84	60.0
86	72.5
88	77.5
90	82.5

D. Curves and Waveforms

The above result is drawn in curves shown in Figures 31 and 32. The waveforms are shown in the photographic sheets which are taken directly from our oscillograph.

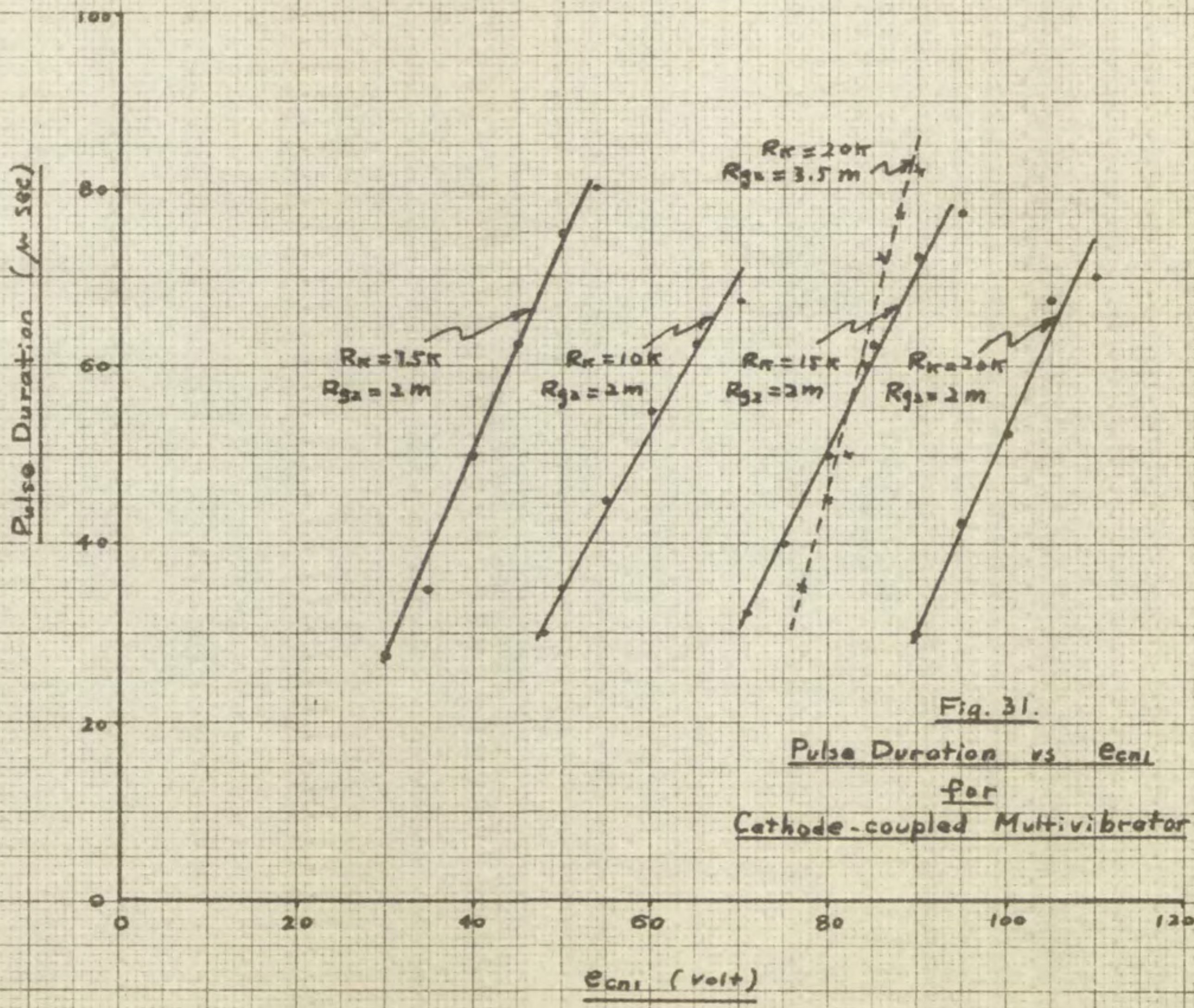


Fig. 31.

Pulse Duration vs e_{cn1}

for

Cathode-coupled Multivibrator

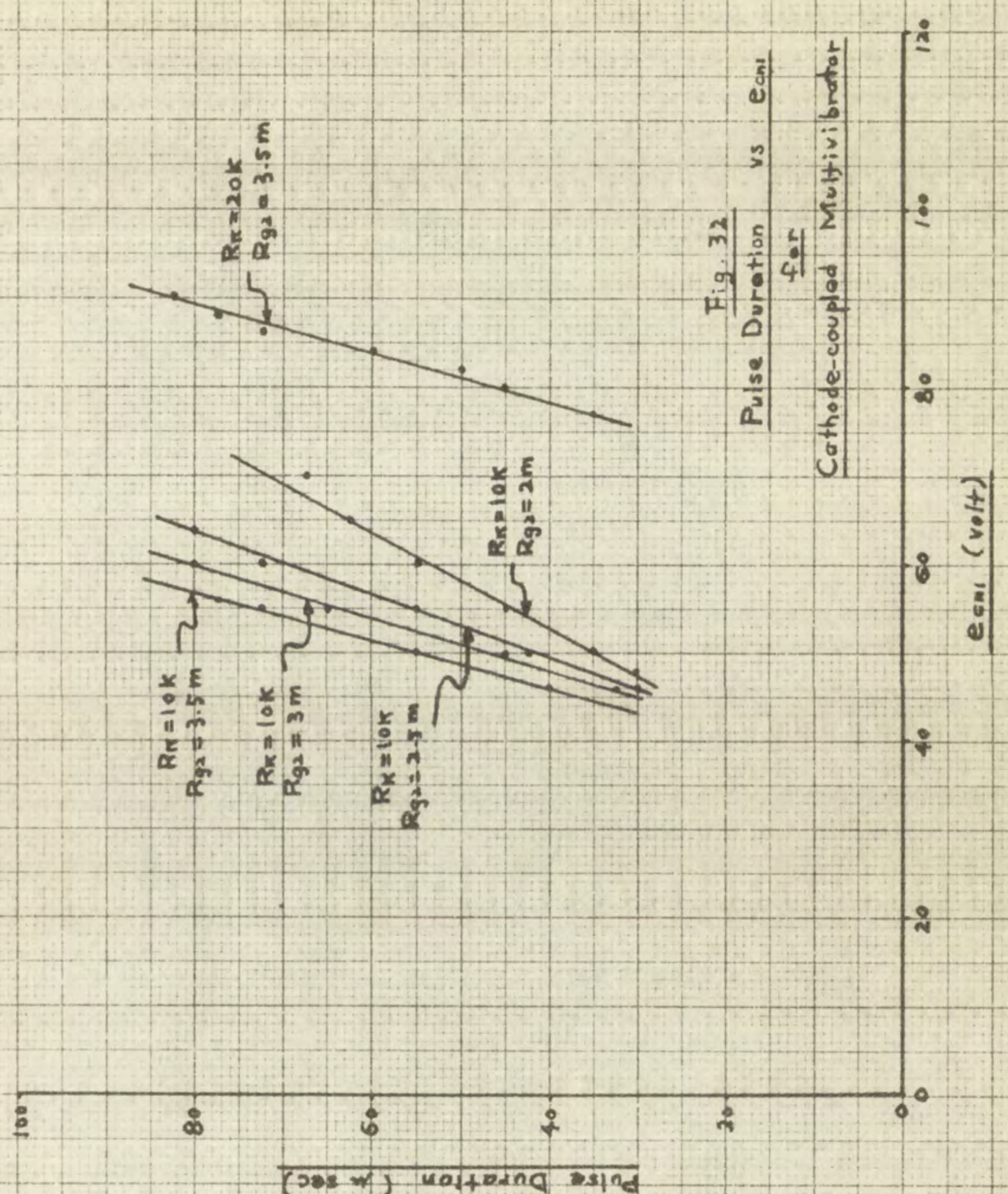
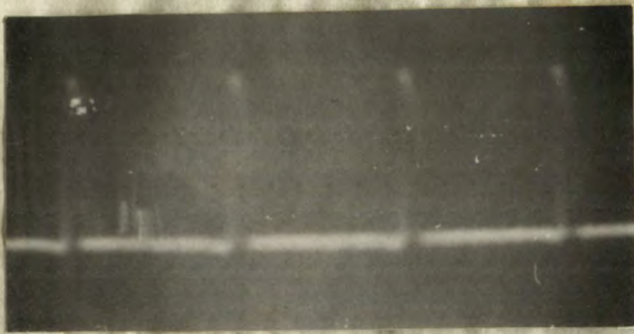


Fig. 32

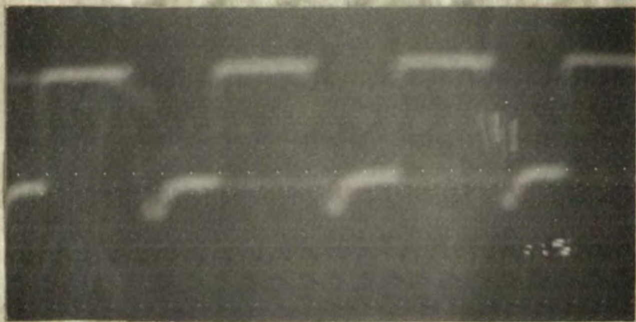
Pulse Duration vs e_{cn1}

for

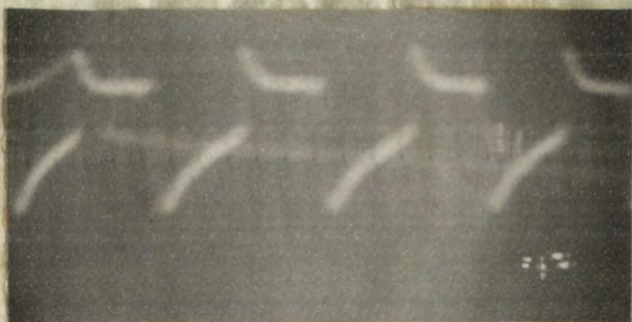
Cathode-coupled Multivibrator



Input Pulse



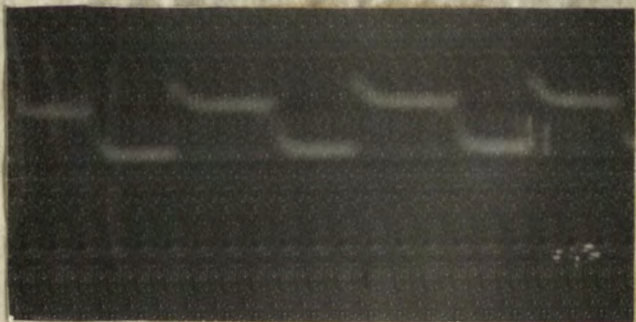
e_{bn1}



e_{cn2}

Waveforms for Cathode-coupled Multivibrator

e_{bn2}



e_{k}

Waveforms for Cathode-coupled Multivibrator

8. Comparison Between the Analytic Result and the Experimental Result

By the simplified result which we have obtained in Paragraph 6, we can calculate the pulse duration. We compare this result with the experimental result.

Frequency = 10,000 cycles per second

$R_K = 10K$; $R_{g2} = 2$ meg.

e_{cn1} (Volt)	Pulse Duration Experiment Result (μ sec)	Pulse Duration Analytic Result (μ sec)	Error (%)
48	30.0	52.5	42.8
50	35.0	57.0	38.6
55	45.0	69.5	35.2
60	55.0	87.6	37.2
65	62.5	94.0	33.5
70	67.5	106.0	36.3

9. Conclusion and Discussion

A. If the circuit parameters satisfy the following conditions:

(1) $\mu > 20$

(2) $\frac{1}{2}R_{L1} = R_{L2} = \bar{r}_p = R_K$

We can calculate the pulse duration by using the formula

$$t = C_2 R_{g2} \ln \frac{\frac{2}{3} + 2\frac{e_{cn1}}{E_{bb}}}{1 - \frac{e_{cn1}}{E_{bb}}}$$

The error is within 40%. If the above conditions are changed, we can obtain a new simplified formula from the exact formula.

B. From our result we observe that if the cathode resistance R_K increases, the bias voltage e_{cn1} must also increase in order to obtain the same pulse duration. This can be easily be verified by our analytic result. For instance $R_K' = 2R_K = 2R$

$$t = C_2 R_{g2} \ln \frac{E_{bb}(R_{L2}+\bar{r}_p)(2R_{L1}+\bar{r}_p+\mu R_K') + R_{L1}R_K' E_{bb} + \mu e_{cn1}' R_{L1}(R_{L2}+\bar{r}_p+R_K')}{(1-\frac{1}{\mu})(R_{L2}+\bar{r}_p+R_K')\left[E_{bb}(R_{L1}+\bar{r}_p+\mu R_K'-R_K') - \mu e_{cn1}' R_K'\right]}$$

$$= C_2 R_{g2} \ln \frac{E_{bb}\left[2R(2\mu+5)R+4R^2\right] + e_{cn1}'\left[2\mu R(4R)\right]}{E_{bb}\left[4R^2(2\mu+1)\right] - e_{cn1}'\left[8\mu R^2\right]}$$

$$= C_2 R_{g2} \ln \frac{(2\mu+7)E_{bb} + 4\mu e_{cn1}'}{2(2\mu+1)E_{bb} - 4\mu e_{cn1}'}$$

$$= C_2 R_{g2} \ln \frac{1 + \frac{4\mu}{2\mu+7} \frac{e_{cn1}'}{E_{bb}}}{\frac{2(2\mu+1)}{2\mu+7} - \frac{4\mu}{2\mu+7} \frac{e_{cn1}'}{E_{bb}}}$$

$$= C_2 R_{g2} \ln \frac{1 + 2 \frac{e_{cn1}'}{E_{bb}}}{2 - 2 \frac{e_{cn1}'}{E_{bb}}}$$

$$= C_2 R_{g2} \ln \frac{\frac{1}{2} + \frac{e_{cn1}'}{E_{bb}}}{1 - \frac{e_{cn1}'}{E_{bb}}}$$

Compare with the original formula. It is evident that $e_{cn1}' > e_{cn1}$.

C. From Figure 32 we observe that the pulse duration increases when R_{g2} increases. Or we can say the pulse duration increases when the time constant increases. This can be readily concluded from our analytic result although the relation is not exactly linear.

D. From the comparison between the analytic results and experimental results it is seen that the deviation is about 40%. This deviation could be due the following reasons:

(1) In our analysis it is assumed that the plate characteristics are linear and equally spaced. This is not true in the region near cut-off where the grid swing actually reaches. Therefore it leads to deviation.

(2) The relation between the cut-off voltage and the plate

$$\frac{[illegible]}{[illegible]} = c_s R_{gs} R_m$$

$$\frac{[illegible] + 1}{[illegible] - 2} = c_s R_{gs} R_m$$

$$\frac{\frac{R_m}{R_{gs}} + \frac{1}{2}}{\frac{R_m}{R_{gs}} - 1} = c_s R_{gs} R_m$$

Compare with the original formula. It is evident that [illegible].

a. From Figure 32 we observe that the pulse [illegible] increases when R_{gs} increases. Or we can say the pulse [illegible] increases when the time constant increases. This can be [illegible] the analytic result although the relation is not exactly linear.

b. From the comparison between the analytic results and the experimental results it is seen that the deviation is [illegible]. This deviation could be due the following reasons:

(1) In our analysis it is assumed that the plate characteristics are linear and equally spaced. This is not true in the region near cut-off where the grid swing actually reaches. Therefore it could be deviation.

(2) The relation between the [illegible] and the pulse

voltage

$$e_{co} = \frac{1}{\mu} e_b$$

which is employed in the analysis, is also an approximation.

(3) Approximation has also been made in obtaining the simplified formula from the exact formula

(4) Inter-electrodes capacitances, which are neglected in the analysis, might also effect the result. When the condenser C_2 is charging, the grid voltage of tube 2 is increasing until it reaches the cut-off value. Now if there is an inter-electrode capacitance between the grid and the plate, the plate voltage of tube 2 will increase when the grid voltage is increasing. This increase of the plate voltage will change the cut-off voltage and, therefore, will change the pulse duration.

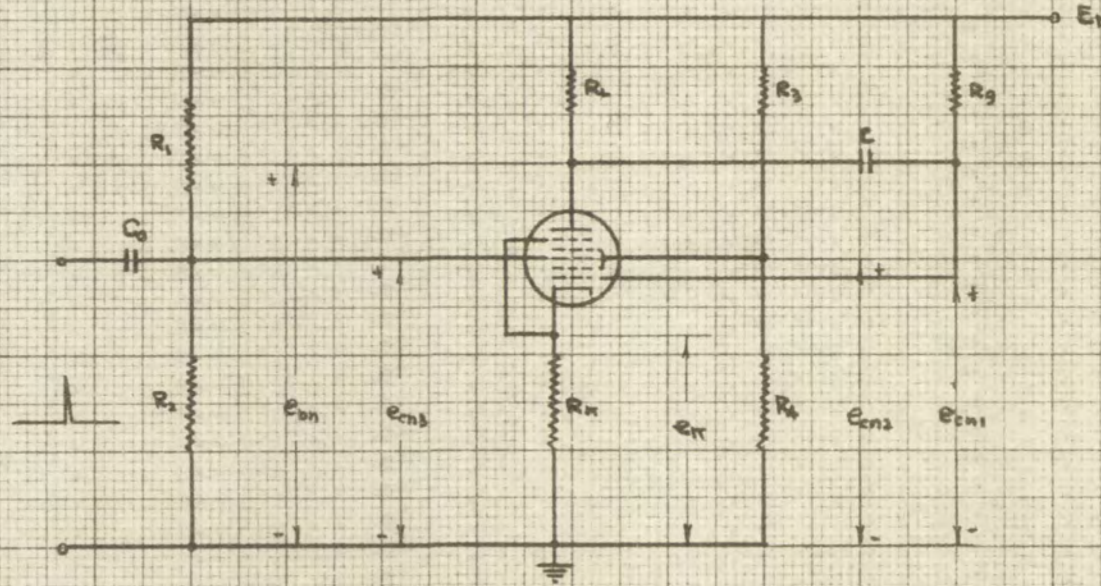


Fig. 33 Phantastron Delay Circuit

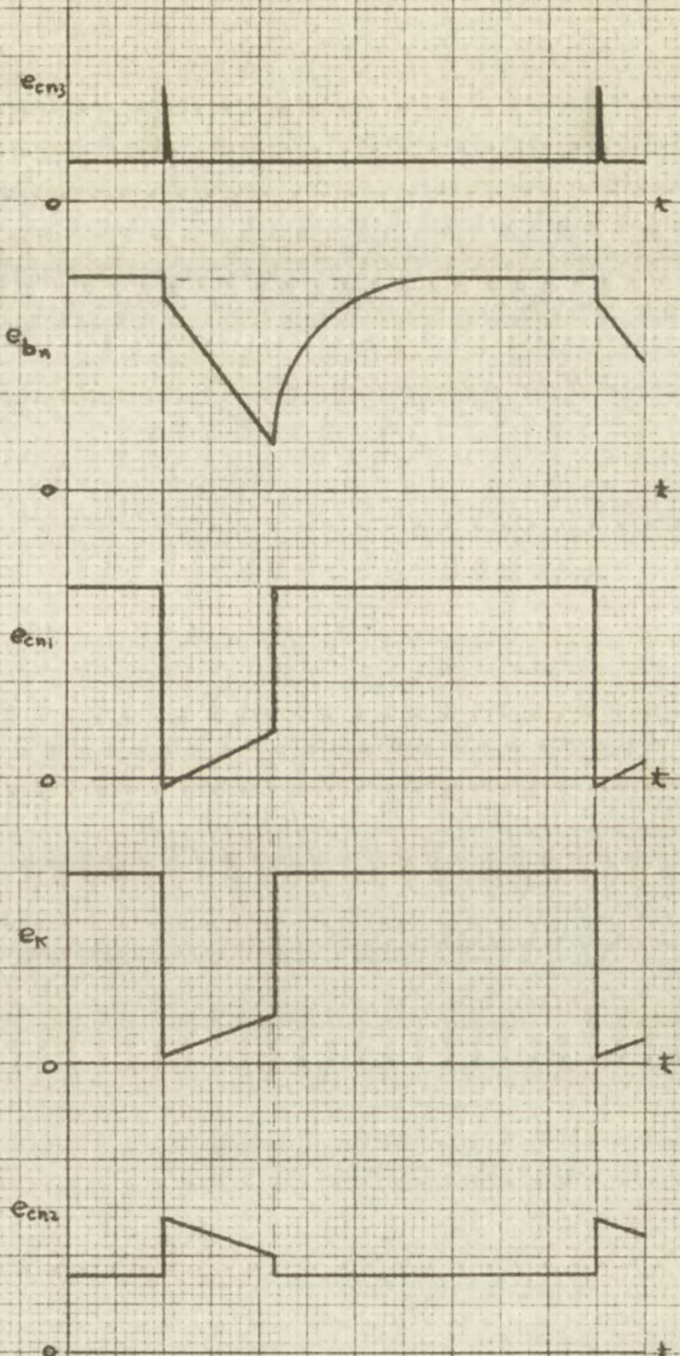


Fig. 34. Waveform for Phantastron Circuit

III. PHANTASTRON CIRCUIT

A phantastron circuit is shown in Figure 33. The tube, 6SA7, is a pentagrid tube which has five grids. Grid 5 is directly connected to the cathode; grid 2 and grid 4 are connected together. This circuit can be treated as a cathode-coupled multivibrator with plate, grid 3, and cathode being considered as tube 1; and grids 2 and 4, grid 1, and cathode being considered as tube 2. They are cathode-coupled. At the normal condition, that is before the trigger pulse is applied, grid 1 returns to positive potential, its value is almost zero since R is very large. Therefore the tube conducts; a part of the current flows through grids 2 and 4, and the other part flows through the plate. However the current passing through the cathode resistor produces a negative voltage large enough to overcome the fixed positive bias on grid 3 and makes grid 3 highly negative. This negative voltage on grid 3 prevents electrons reaching the plate. This is equivalent to the condition in the cathode-coupled multivibrator when tube 2 conducts and tube 1 cuts off.

When a positive pulse is applied to grid 3, grid 3 becomes positive so that electrons can pass through and reach the plate. The voltage between the plate and the cathode drops suddenly, and because of the presence of the condenser the voltage between grid 1 and the cathode drops accordingly. The current through grids 2 and 4 reduces. Here the situation is different from the cathode-coupled multivibrator. In the cathode-coupled multivibrator the grid voltage of tube 2

III. [illegible]

A pentagrid circuit is given in Figure [illegible]. [illegible]

is a pentagrid tube which has five grids. [illegible]

to the cathode; grids 2 and 4 are connected together. [illegible]

can be treated as a cathode-coupled [illegible]

and cathode being considered as tube 1, and grid 3 [illegible]

cathode being considered as tube 2. [illegible]

normal condition, that is before the [illegible]

1 returns to [illegible]

very large. Therefore [illegible]

through grids 2 and 4, and [illegible]

However the current [illegible]

negative voltage [illegible]

grid 3 and [illegible]

3 prevents electrons reaching the plate. This is [illegible]

condition in the [illegible]

and tube 1 cuts off.

When a [illegible]

positive so that [illegible]

voltage between the [illegible]

of the presence of [illegible]

cathode drops [illegible]

Here the situation [illegible]

tor. In the cathode-coupled [illegible]

drops sufficiently to cut tube 2 off. In phantastron circuit if the voltage between grid 1 and the cathode drops sufficiently to prevent electrons from reaching grid 2 and 4, it will also prevent electrons from reaching the plate.

Now, the condenser starts charging, the voltage between grid 1 and cathode begins to increase and so does the current through grids 2 and 4 until the voltage drop in cathode resistor large enough to cut the plate current off and the original condition restores.

A cathode follower is usually added to the phantastron circuit for reducing the time required for recharging condenser between pulses. A diode is also added for controlling the pulse duration.

D.I.