DOUBLE MODULATION OF A PULSE CARRIER

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PREFACE

For the past several years the companies in the seismograph business have been turning more and more to the use of magnetic tape recording systems.

This thesis has as its purpose a discussion of a system which has been designed to facillitate the recording of two seismic information signals on one magnetic tape channel, thereby doubling the capacity of existing recorders. The design, operation and testing of the actual circuits are covered in the paper. These circuits are taken from a patent application which I have assigned to the Esso Research and Engineering Company.

An expression of appreciation is made for the guidance and help of Dr. H. L. Jones. I would also like to express my deepest appreciation to Dr. K. N. Burns, Dr. H. B. Ferguson, and Mr. W. L. Ikard for their technical assistance and advice, and to The Carter Oil Company Research Laboratory for the use of equipment and material used in building and testing the apparatus.

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CHAPTER I

THE RECORDING OF SEISMIC INFORMATION

In petroleum seismic exploration, it is customary to detonate an explosive charge in a relatively shallow hole in the ground to produce complex waves in the earth, part of which penetrate the ground to a considerable distance, are reflected from subterranean geological strata, and are propagated back toward the surface of the earth. These reflected waves are of interest to geologists. When properly recorded, they enable the subterranean formations to be predicted with a considerable degree of accuracy. The translational movement of the earth resulting from the reflected waves is converted by geophones, or seismometers, to electrical currents representative of the movement. The electrical signals from the geophones are amplified, filtered, and recorded in some manner to allow visual observation of something representative of the movement of the earth.

The apparatus described in this paper is aimed toward further simplification of the equipment used in seismograph recording.

From the early days of the exploration seismograph industry until the late 1940's the information signals from geophones were recorded with galvanometer type oscillographic recorders. The records obtained were on photographic paper with the signals appearing as "wiggly" traces. Figure 1 shows an example of such a record.

The desirability of reproducing the electrical signal from the

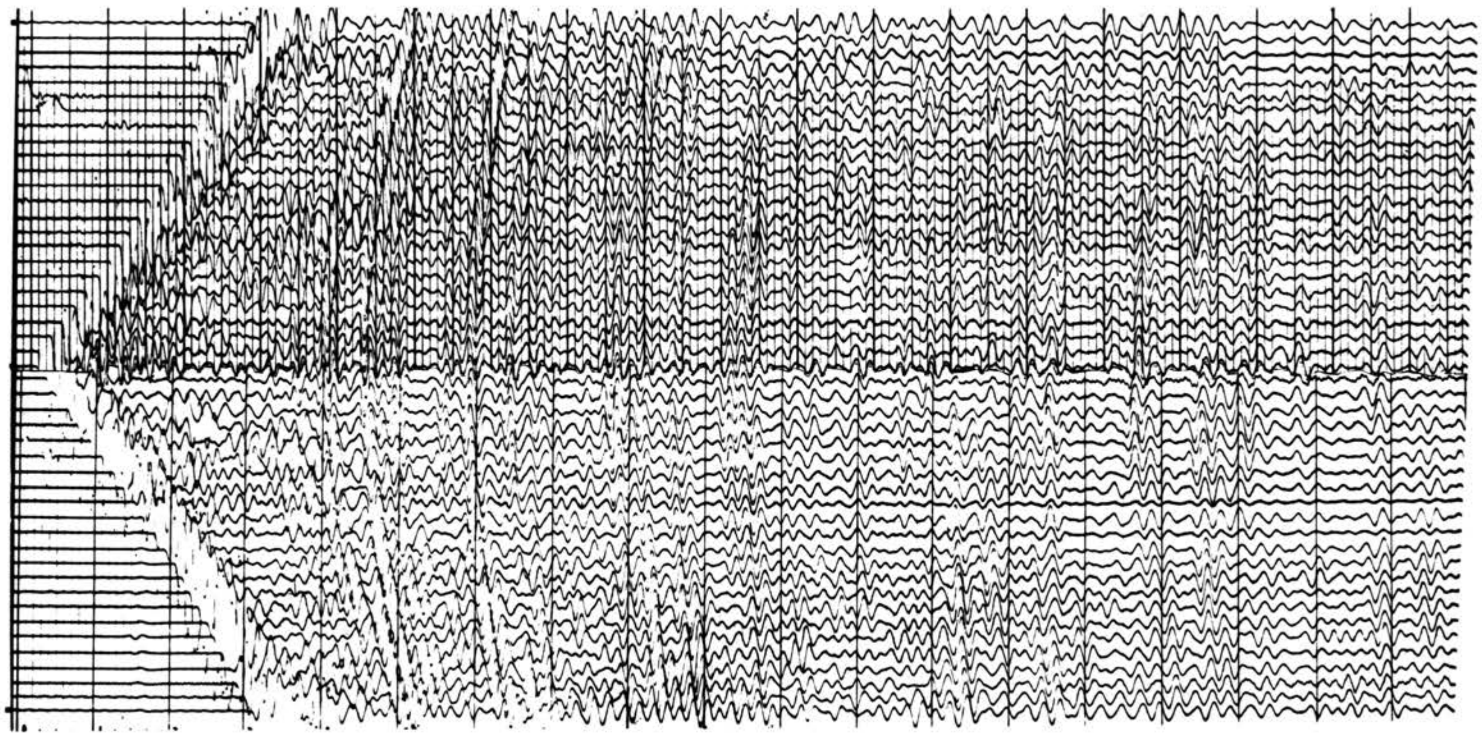

Figure 1.
Typical Seismic Record

record and for reducing the size and weight of the instruments led to the search for different methods of recording the information. Two of the methods used to obtain reproducible records were called variable area and variable density recording. Both of these systems utilized the galvanometer oscillographic recorders with special changes to put the desired signal on photographic film.

In the early 1950's another recording medium was introduced to the seismic industry. The success of magnetic tape recording in audio work made the system seem very attractive for seismic recording. The magnetic tape system offered the advantages of reproducible records and elimination of photographic processing in the field. In cases where the terrain necessitates portable operations, the latter advantage was especially appreciated.

The frequencies of the waves of interest in seismic work are between ten cycles per second and two hundred fifty cycles per second, with most records ranging only from twenty to one hundred cycles per second. This frequency range made the direct recording of the signals on magnetic tape impractical. The seismograph companies who built magnetic tape equipment used various modulation systems to record the information. The systems used include frequency modulation, pulse width modulation, and bias recording, with the first two receiving the most use.

At the present time magnetic tape recorders are being used extensively in the seismograph work being carried on around the world.

CHAPTER II

INCREASING THE UTILITY OF RECORDERS

The various magnetic tape recorders built for seismic use are similar in many respects. Most of them have a peak signal to peak noise ratio of about 46 db., or 200:1. Most of the recorders were designed to record about 30 separate signals for from two to six seconds.

There are times when it would be desirable to have more signal channels available, either to record signals from more geophones, or to record some of the control voltage information, that is, to record the voltages used in the automatic gain control circuits. Of course it would be most desirable to do this without increasing the size or amount of equipment used.

The subject of this paper is a method of doubling the number of signals which can be recorded without using any more recording heads or magnetic tape than are presently in use.

The method of accomplishing this is to modulate two parameters of a single pulse carrier. One of the information signals is used to vary the repetition rate of the carrier pulses. The other information signal is used to modulate the duration time of the carrier pulses. In effect, this is a combination of frequency modulation and pulse width modulation.

The circuits shown and discussed in this paper are covered by a patent application which has been assigned by the author to the Esso Research and Engineering Company.

If the system is to be usable it must meet several requirements. First, the frequency response must be similar to that of regular seismic equipment. For most uses a response that is flat from ten to one hundred cycles per second is sufficient. Second, the signal to noise ratio should be as good as the regular seismic magnetic tape recorders. In most recorders this ratio is about 200:1. The third requirement is the crosstalk should not be significant. This means it would be preferable to have it as low as the noise.

The following chapters will give detailed explanations of the prototype model of the circuits used and the results of tests that have been made on them.

CHAPTER III

DESCRIPTION OF CIRCUITS USED

As has been previously stated, the purposes of the circuits, which are the subject of this paper, are to modulate and demodulate a pulse carrier with two separate information signals. This will provide a modulated carrier signal suitable for application to a magnetic tape recording head and for recovery from the magnetic tape. The demodulator will reconstruct the original information signals.

A simple description of the modulator circuit can be presented with the aid of the block diagram shown in Figure 2. Examining the path of the signal which ultimately varies the repetition rate of the carrier, it can be seen that the beginning is labled "F. M. Input". The first block, representing an amplifier stage, is followed by an astable multivibrator, the frequency of which is a linear function of the voltage amplitude of the information signal. The output of the multivibrator is amplified and differentiated in the section labled "Diff. Circuit". The output of the differentiating circuit is fed to the trigger circuit which triggers the mono-stable multivibrator, which is the final output tube.

The term "mono-stable multivibrator" is used to refer to a multivibrator circuit which has a stable operating condition with one tube conducting and the other tube non-conducting. Only when a trigger pulse is received do the tubes change operating conditions, and then for

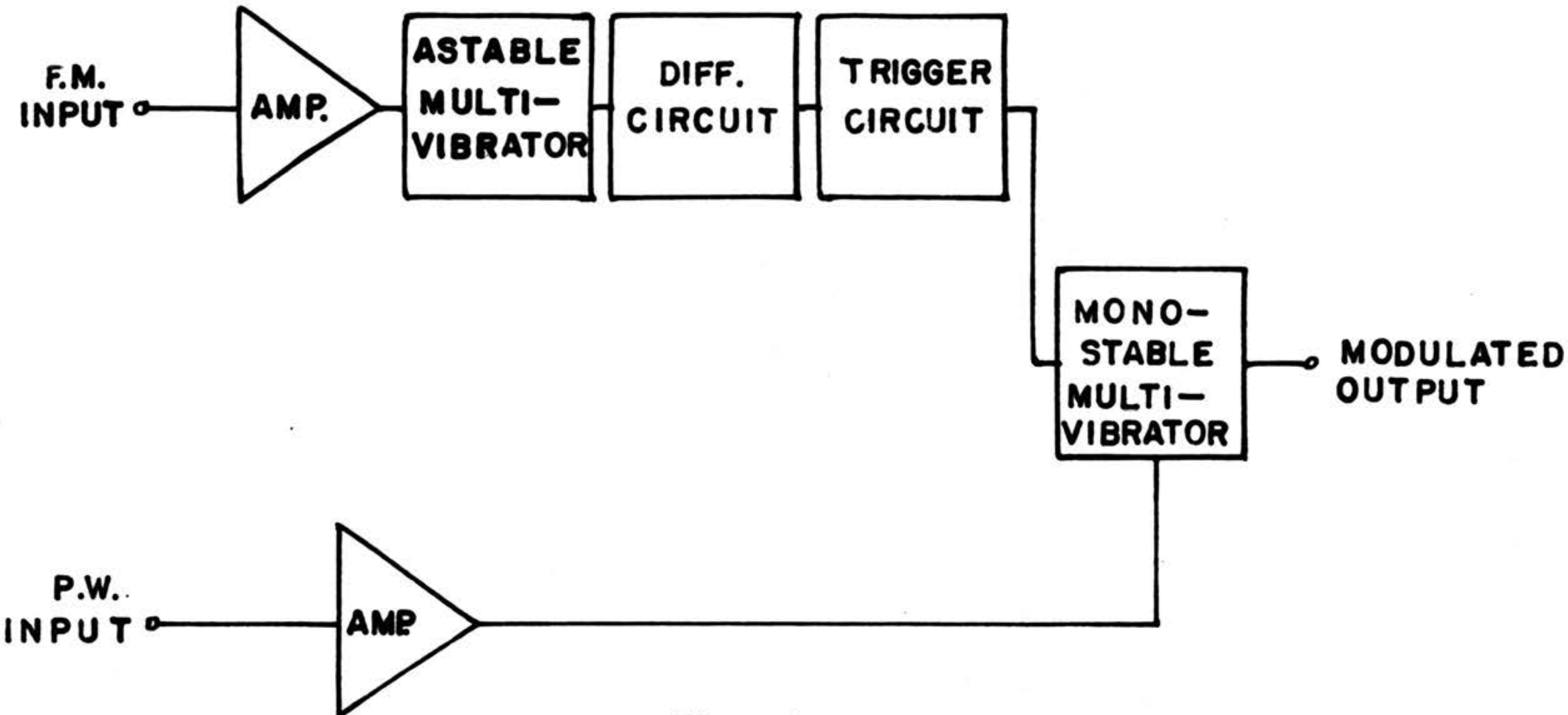

Figure 2.
Modulator Block Diagram

a period determined by the circuit paramaters and mostly independent of the trigger. For each trigger received, there is one pulse put out.

The path of the second information signal is somewhat shorter. From the input, labled "P. W. Input", the signal is amplified and fed to the mono-stable multivibrator, where it is used to vary the width of the output pulses.

The output of the modulating circuit can be fed to a conventional magnetic tape recording head which applies the signal to the magnetic tape.

The demodulator is used to recover the information signals from the carrier. A simplified explanation will be offered with the aid of the block diagram in Figure 3. For simplification, the testing of the circuits was made with the signal fed directly from the modulator to the demodulator. If the signal to be demodulated were coming from the reproducing head of a magnetic tape recorder, a pulse reformer such as has been described in Electronics[1] would precede the circuits shown.

The modulated pulse carrier is fed to the first block labled "Separator". The separator is a conventional phase splitter amplifier whose function is to give two output waveforms, one with the positive voltage swing a function of the leading edge of the input pulse and the other with the positive voltage swing a function of the trailing edge of the input pulse. To demodulate the frequency modulated part of the signal, the pulse labled "Leading edge pulse" is differentiated

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[1]Max L. Van Doren, "Magnetic Recording of P. W. M. Signals", Electronics, May 1954, pp.232-242.

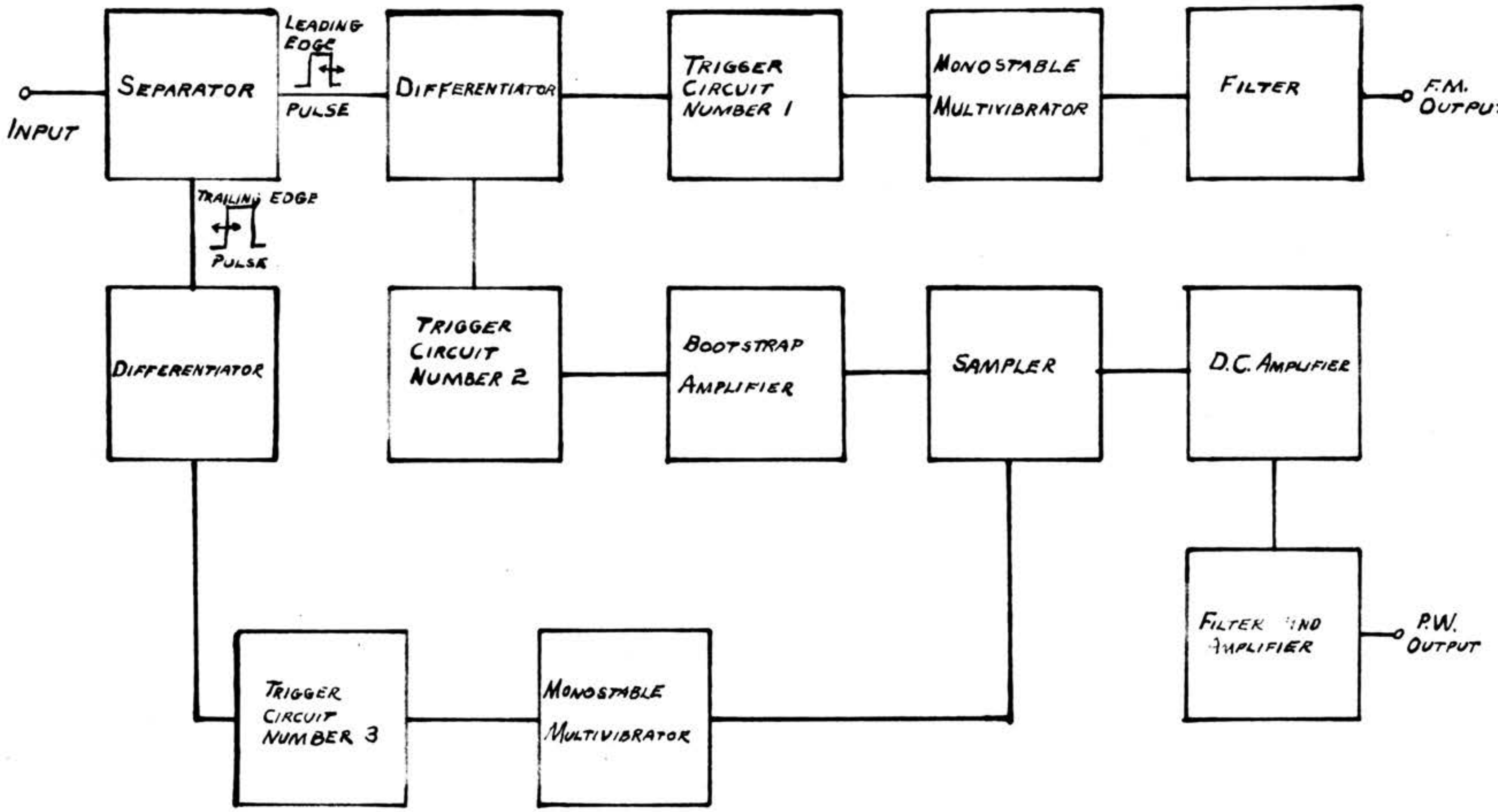

Figure 3. Block Diagram of Demodulator

and fed to "Trigger circuit number 1". The trigger circuit functions to operate the mono-stable multivibrator. The output pulses of the multivibrator are filtered and the output is obtained in the same form as when it was fed to the input of the modulator.

The pulse width demodulator is rather more complicated than the frequency modulation demodulator. After differentiation, the leading edge of the input wave is fed to the block labled "Trigger circuit number 2". This trigger circuit acts on the "bootstrap amplifier", which starts a capacitor charging linearly with respect to time. The trailing edge of the input wave is differentiated and used to trigger a mono-stable multivibrator. The output of this multivibrator is fed to a block labled "Sampler", which lets the instantaneous voltage of the bootsrap amplifier through the D. C. amplifier and filter to the final amplifier output. The output signal is identical to the signal fed to the P. W. Input of the modulator.

A more detailed explanation of the modulating circuit will be given with the aid of Figure 4. As before, the frequency modulator will be discussed first. The information signal is fed in the F. M. Input to tube V101, which is a conventional R C Amplifier. The output of this amplifier is coupled to the junction of the biasing voltage divider, R_4 and R_5, and the grid resistors, R_6 and R_7, of the astable multivibrator, tubes V103 and V104. This multivibrator is a well known, degenerative, positive-bias multivibrator. As shown in Figure 5, the frequency vs. grid voltage curve is quite linear from 1000 cycles per second to 3000 cycles per second. The output of the multivibrator is a square wave type signal with a repetition rate dependent on the amplitude of the grid voltage. The output of the multivibrator is

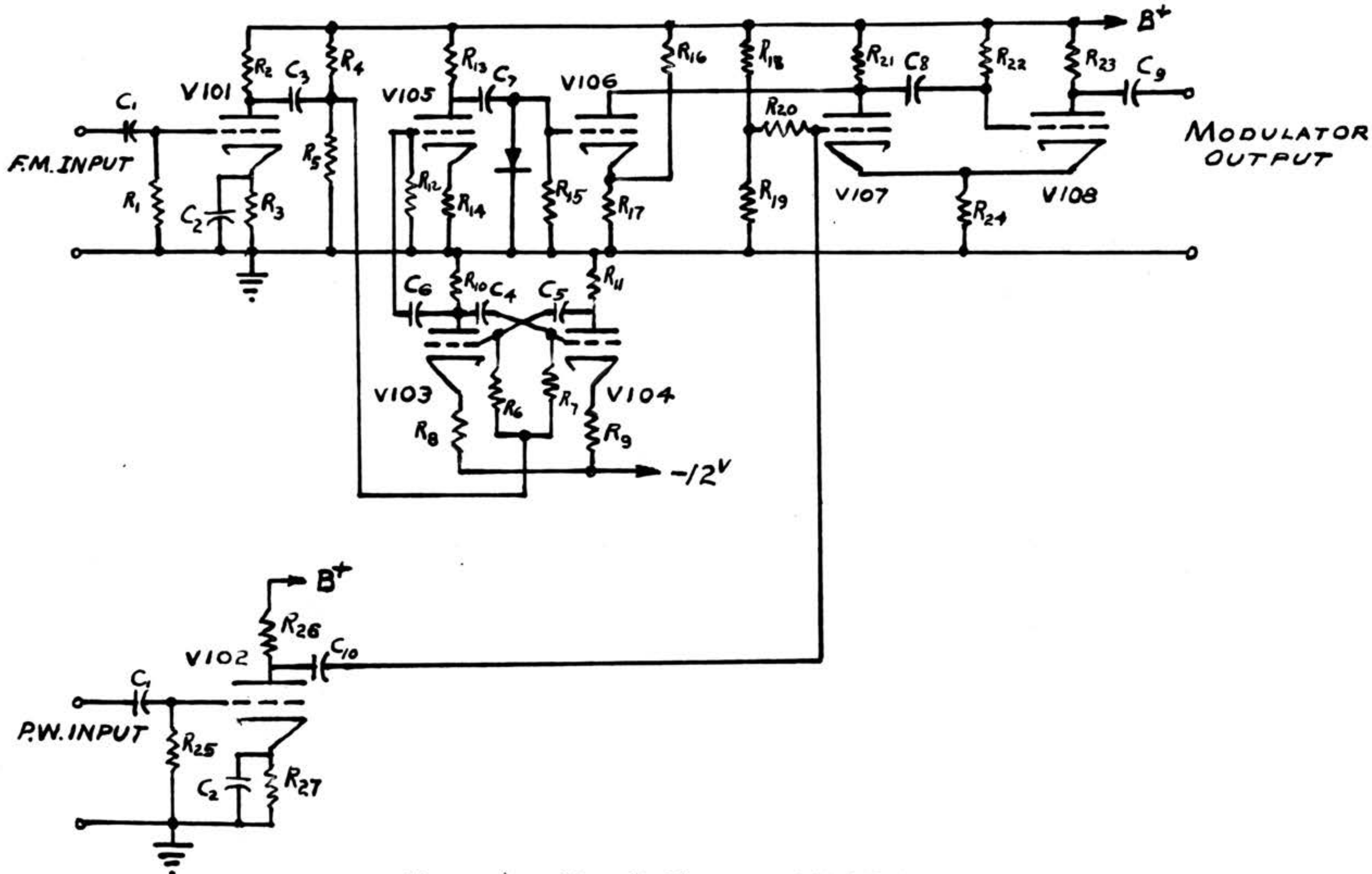

Figure 4. Circuit Diagram of Modulator

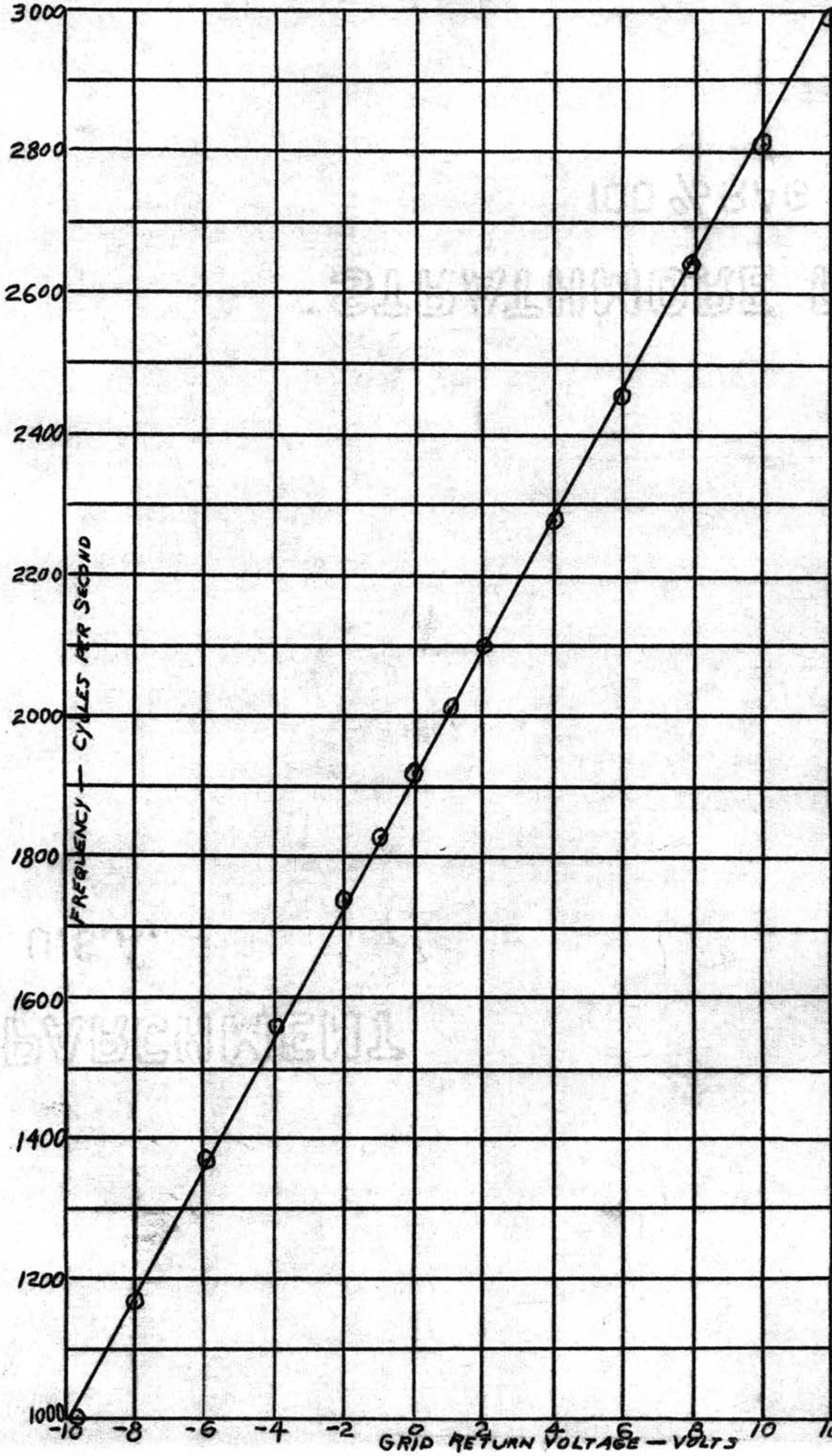

Figure 5. Frequency vs. Grid Return Voltage

amplified by tube V105. The square wave output of V105 is then differentiated by the circuit $C_7 - R_{15}$. The positive pulse is applied to the grid of tube V106, which is used to trigger the modulating mono-stable multivibrator, tubes V107 and V108. The mono-stable multivibrator has as an output one pulse, with steep leading and trailing edges, for each trigger pulse fed to it. The duration of the individual pulse is independent of the trigger pulse, and will be discussed in the following paragraphs. To summarize the action of the circuit so far, it can be said that the information signal fed into the F. M. Input acts upon the circuit to vary the repetition rate of the output pulses. The instantaneous repetition rate of the pulses is proportional to the instantaneous voltage of the input. The output signal has a frequency spectrum containing the fundamental carrier frequency, harmonics of the carrier, sum and difference frequencies of the carrier and the information signal, and sum and difference frequencies of the carrier harmonics and the information signal.

The information signal which modulates the duration time of the carrier pulses is fed to the P. W. Input and amplified by tube V102. The output of this amplifier is fed to the grid of tube V107 where it varies the grid voltage, thus varying the time of conduction of tube V107 and the width, or duration time, of the output pulses. The pulse duration time is determined by the grid voltage of V107 and the time constant of R_{22} and C_8. The pulse duration time vs. grid voltage curve is shown in Figure 6. This curve shows a linear response from forty microseconds to two hundred forty microseconds duration time. The pulse duration time is proportional to the instantaneous voltage of the information signal on the grid of tube V107.

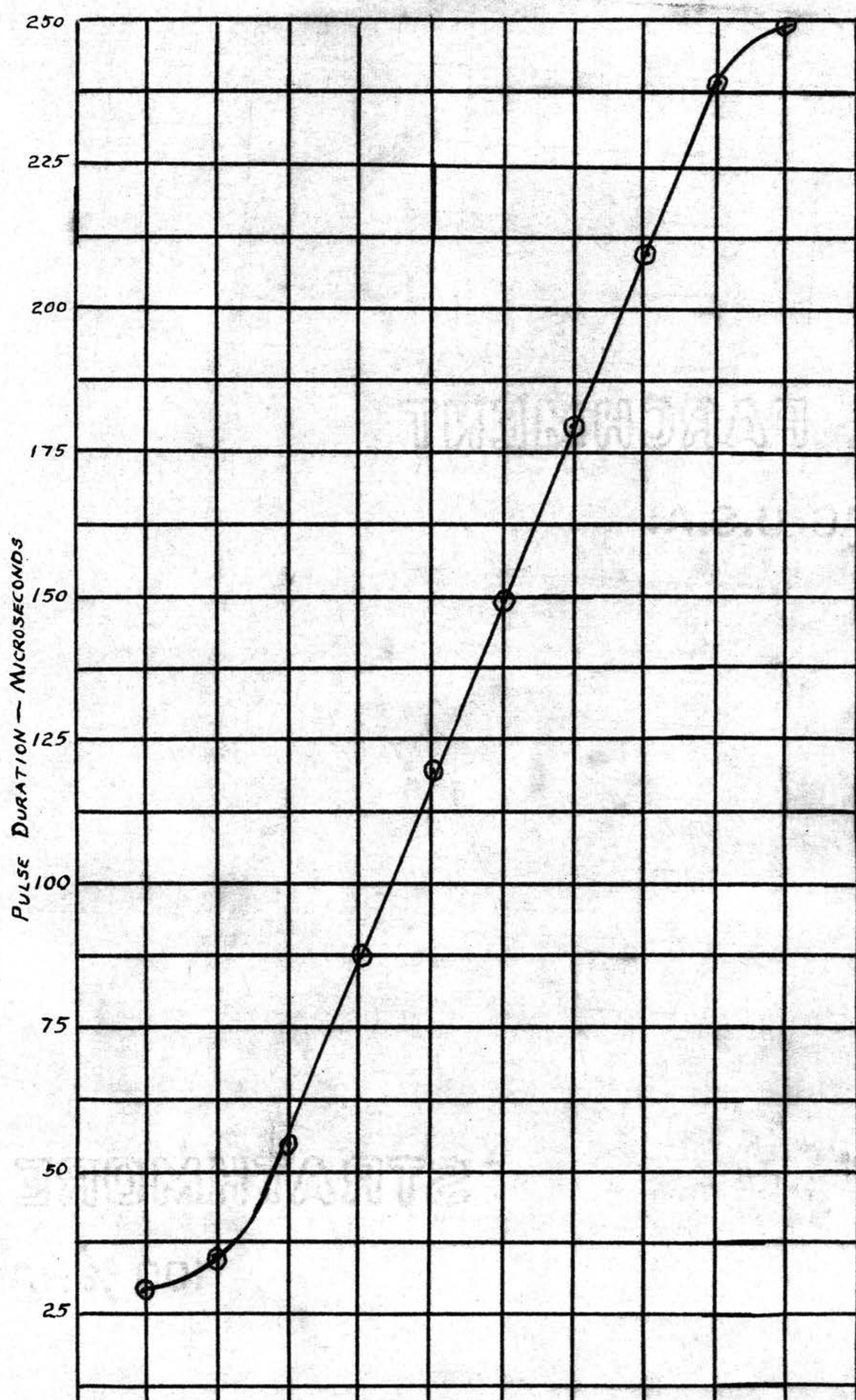

Figure 6. Pulse Duration vs. Grid Voltage

The final output of the modulator is a continuous pulse train of varying repetition rate and pulse duration time. The circuit parameters were chosen so the repetition rate, with no signal applied to the F. M. input, would be about 2200 pulses per second. The modulator will swing this repetition rate down to 1200 and up to 3200 pulses per second. The pulse duration time was set so the pulse duration time with no modulation is 150 microseconds. The modulating signal varies this pulse duration time between the limits of 75 microseconds and 225 microseconds.

A more detailed explanation of the demodulating circuit can be given with the aid of Figure 7. The modulated carrier is placed on the grid of tube V109, which has been called the separator. This seperator tube is an amplifier with approximately unity gain and is commonly known as a "phase splitter". The plate resistor, R_{33}, is equal to the total cathode resistance, which consists of R_{31} plus R_{32}. The output of the plate is 180 degrees out of phase with the output of the cathode. If the input to the demodulator is considered as a series of positive pulses with the pulse duration time modulated so that the trailing edge of the pulse is the variable, then the output of the cathode of tube V109 is also such a signal. The output of the plate circuit can be considered as a series of positive pulses with the leading edge variable, remembering that the leading edges of these pulses coincide in time to the trailing edges of the input pulses.

To pursue the path of the F. M. portion of the signal, the output of the cathode of tube V109 is followed to the capacitor, C_{12}, and the resistor, R_{34}, which constitute a differentiating circuit. The diode, D_1, in parallel with R_{34}, is added to suppress the negative

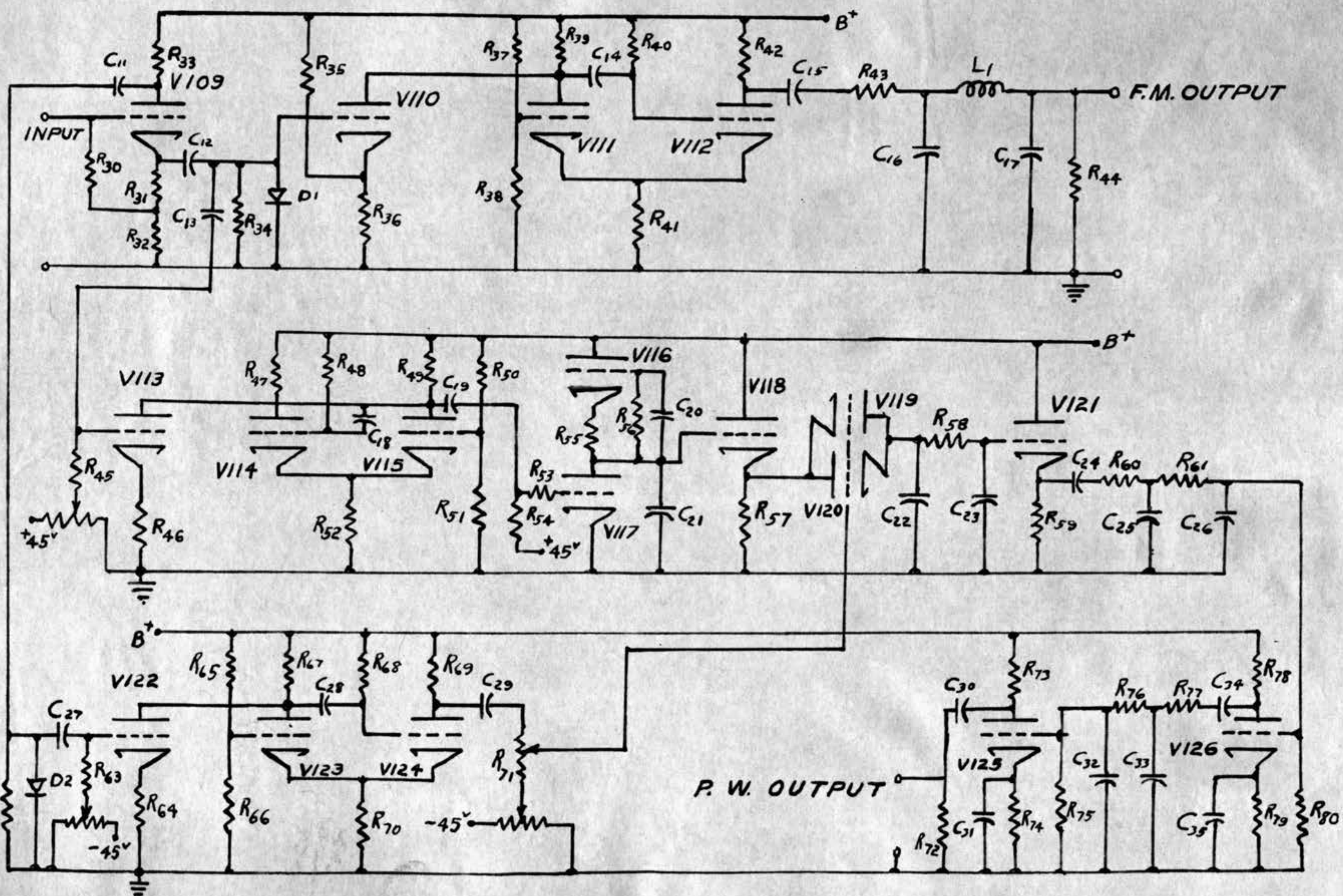

Figure 7. Circuit Diagram of Demodulator

spikes which are contributed by the trailing edges of the pulses. The grid of tube V110 is fed a series of positive spikes developed by the leading edges of the input pulses. The tube V110 is used to trigger the mono-stable multivibrator, tubes V111 and V112. The output of the multivibrator, taken from the plate of tube V112, is a series of pulses of variable repetition rate and of constant pulse duration time. The integrating filter, consisting of R_{43}, C_{16}, L_1, and C_{17}, has as an output the information signal which was originally fed into the F. M. input of the modulating circuit.

The pulse width demodulator uses trigger spikes from both the leading edge and the trailing edge of the input pulses. The positive spike from the leading edge of the pulse, from the cathode of tube V109, is fed through capacitor C_{13} to the grid of tube V113, which triggers the mono-stable multivibrator, tubes V114 and V115. The output of the mono-stable multivibrator, taken from the plate of tube V115, is a negative pulse which is fed to the grid of tube V117. The negative pulse holds V117 in a cutoff, or non-conducting, condition, allowing the capacitor C_{21} to charge linearly in the bootstrap circuit consisting of tube V116, R_{55}, R_{56}, C_{20}, and C_{21}. This bootstrap circuit is a modification of a circuit shown in the literature.[2] As long as the tube V117 is held below cutoff, the capacitor, C_{21}, charges at a linear rate. (Simpler circuits were tried at this point in the demodulator, but were found to give a charging rate across the capacitor which varied when the repetition rate varied.) Since the voltage on C_{21} is fed to the grid of the cathode follower, V118, the voltage on

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[2]Britton Chance et. al., Waveforms, (New York, 1949) p. 270.

R_{57} also rises linearly with time. It should be noted at this point that tubes V119 and V120 are normally biased to cutoff.

At this point it is advisable to return to tube V109 and start following the path of the trailing edge of the input pulse. The output of the plate of tube V109 is differentiated by the capacitor-resistor circuit, C_{11} - R_{62}. As was mentioned before, the positive spikes at this point were derived from what were the trailing edges of the original modulated pulses. These positive spikes are applied to the grid of tube V122, which triggers the mono-stable multivibrator, tubes V123 and V124. The output of tube V124 is a positive pulse of short duration which is applied to the grids of tubes V119 and V120. When these sampler tubes conduct they allow the capacitor, C_{22}, to assume the instantaneous voltage on resistor R_{57}. This means, in effect, that the voltage on capacitor C_{22} is determined by the pulse duration time of each pulse. The leading edge of the pulse starts the linear voltage increase across R_{57}, and the trailing edge of the pulse determines when that voltage is sampled by the capacitor, C_{22}. The capacitor essentially holds its charge until the next sampling pulse allows a change. The resistor, R_{58}, and capacitor C_{23}, integrate the voltage on C_{22} and apply it to the grid of V121. The output of V121 is filtered and amplified by tubes V126 and V125 and associated components to give the final output of tube V125 as the signal originally used to modulate the duration time of the carrier pulses. The action of tubes V118, V119, V120, and V121 has been discussed in an instrument instruction manual.[3]

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[3] Houston Technical Laboratories, Bulletin No. 81371, pp. 4-10.

CHAPTER IV

FREQUENCY CALCULATIONS FOR ASTABLE MULTIVIBRATOR

The circuit which was used for the frequency modulator is a positive-bias, degenerative feedback multivibrator which has been described in the literature. The equations used in the following discussion of the circuit were taken from one of the articles on the subject.[4] The following discussion demonstrates the method of calculating the center frequency of the multivibrator and shows how to determine the degreeof linearity of the modulating system.

The circuit used in the modulator is redrawn in Figure 8, with the values of the various circuit parameters shown.

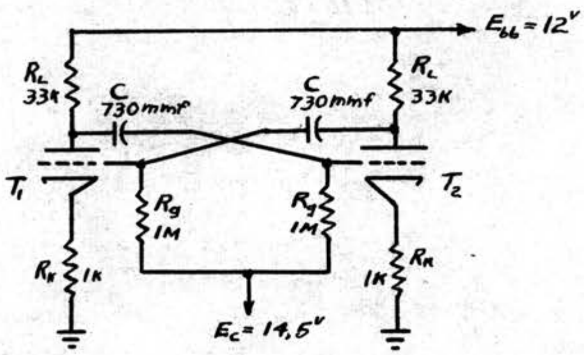

Figure 8. Astable Multivibrator

The ideal waveforms shown in Figure 9 will help to explain the various voltage values used in the equations which follow.

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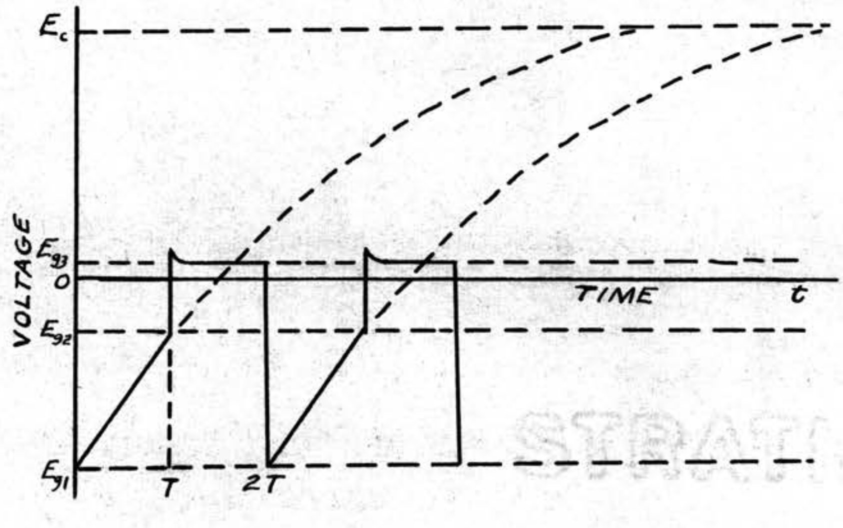
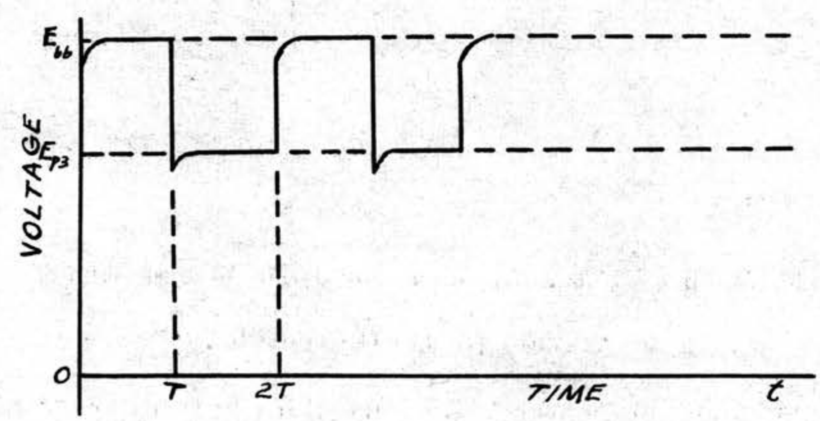
[4]Sidney Bertram, "The Degenerative Positive-Bias Multivibrator", Proceedings of the I. R. E., Vol. 36, Feb. 1948, pp.277-280.



(a) Voltage on grid of T_1 vs. time



(b) Voltage on plate on T_1 vs. time

Figure 9. Waveforms for multivibrator

When one of the tubes, such as T_2, starts conducting, the other tube is rapidly driven below cutoff, and stays cutoff until the grid charges up through the grid return resistor and the coupling capacitor to the point of conduction. At this point the two tubes reverse operating conditions, with tube T_1 conducting and driving $T_2$to cutoff.

The equation which expresses the voltage on the grid of the tube as it reses exponentially with time from its maximum negative value, taken at time t=0, is :

$$e_g = E_c - (E_c - E_{g1})\varepsilon^{-\frac{t}{R_g C_e}} \qquad (1)$$

In equation 1, C_e is the effective capacitance, $C_e = C + C_{in}$, where $C_{in} = C_{gk} + C_{pk} + C_s$. In this example, C is large enough to make the effects of the interelectrode and stray capacities negligible. For a 12AU7 tube the approximate values of C_{gk} and C_{gp} are 1.6 mmfd. and 1.5 mmfd.

Referring to Figure 20, the circuit will flip over, or T_1 will start conduction, when the grid of T_1 reaches the cutoff voltage, $E_{g2} = -\frac{E_{bb}}{\mu}$. For a symmetrical system, the value of t for this condition is the half period, T, of the multivibrator. By measurement on the actual circuit the cutoff voltage was determined to be - 3 volts.

The maximum negative voltage of the grid is given by equation 2.

$$E_{g1} = E_{g3} - (E_{bb} - E_{p3})\left(\frac{C}{C + C'_{in}}\right) \qquad (2)$$

This equation states that the grid starts at a voltage equal to the cathode voltage, during conduction, E_{g3}, and is driven down by an amount equal to the voltage drop across the load resistor of the other tube, $E_{bb} - E_{p3}$, modified by the factor $\frac{C}{C + C'_{in}}$.

$$E_{g3} = \frac{R_k}{R_1 + R_k + r_p} E_{bb} \qquad (3)$$

$$E_{bb} - E_{p3} = \frac{R_1}{R_1 + R_k + r_p} E_{bb} \qquad (4)$$

$$C'_{in} \approx C_{gk} + 2C_{gp} + C_s \qquad (5)$$

For this particular circuit, $C \gg C'_{in}$ and $\frac{C}{C + C'_{in}} \approx 1$.

Substituting numerical values:

$$E_{g3} = \frac{1000}{33{,}000 + 1000 + 6000} \cdot 12 = 0.3 \text{ volts}$$

$$E_{bb} - E_{g3} = \frac{33{,}000}{33{,}000 + 1000 + 6000} \cdot 12 = 9.9 \text{ volts}$$

The value for r_p is an approximation taken from a tube manual. Substituting the numerical values in equation 2 gives:

$$E_{g1} = 0.3 - 9.9 = - 9.6 \text{ volts}$$

Using equation 1 to determine the time constant for $e_g = E_{g2}$:

$$- 3 = 14.5 - (14.5 + 9.6)\varepsilon^{-\frac{T}{R_g C}}$$

$$\varepsilon^{-\frac{T}{R_g C}} = \frac{17.5}{24.1} = 0.726$$

$$\frac{T}{R_g C} = 0.321$$

$$T = 0.321 R_g C = 0.321 \cdot 1 \cdot 10^6 \cdot 730 \cdot 10^{-12}$$

$$T = 234 \cdot 10^{-6}$$

Since this value of t is the half period of the multivibrator, the repetition rate, or the fundamental frequency, f, is

$$f = \frac{1}{2\,T} = \frac{1}{2 \cdot 234 \cdot 10^{-6}} = 2130 \text{ cycles per second}$$

This is in good agreement with the measured value of 2200 cycles per second in the actual circuit.

To demonstrate the linearity which can be obtained with this circuit, equation 1 is used as a starting point:

$$e_g = E_c - (E_c - E_{g1})\varepsilon^{-\frac{t}{R\,C}} \qquad (1)$$

$$\varepsilon^{-\frac{t}{R\,C}} = - \frac{e_g - E_c}{E_c - E_{g1}}$$

$$E_{g2} = \text{cutoff value of } e_g = - \frac{E_{bb}}{\mu}$$

$$\varepsilon^{-\frac{T}{R\,C}} = - \frac{-\frac{E_{bb}}{\mu} - E_c}{E_c - E_{g1}}$$

$$\varepsilon^{\frac{T}{R\,C}} = \frac{E_c - E_{g1}}{\frac{E_{bb}}{\mu} + E_c} = \frac{\frac{E_c}{E_{bb}} - \frac{E_{g1}}{E_{bb}}}{\frac{1}{\mu} + \frac{E_c}{E_{bb}}}$$

Let $\beta = \frac{E_c}{E_{bb}}$ and $\gamma = \frac{E_{g1}}{E_{bb}}$

then

$$\varepsilon^{\frac{T}{RC}} = \frac{\beta - \gamma'}{\frac{1}{\mu} + \beta} = \frac{\mu(\beta - \gamma')}{\mu\beta + 1}$$

$$\frac{T}{RC} = \ln \frac{\mu(\beta - \gamma')}{\mu\beta + 1}$$

$$f = \frac{1}{2T} = \frac{1}{2RC \ln \frac{\mu(\beta - \gamma')}{\mu\beta + 1}} \tag{6}$$

Let β_0 be the center of the operating range of β and x be the deviation from the center, i. e., $\beta = \beta_0 + x$. Substituting these values:

$$f = \frac{1}{2RC \ln \frac{\mu(\beta_0 + x - \gamma')}{\mu(\beta_0 + x) + 1}}$$

$$f = \frac{1}{2RC \ln \frac{\mu(\beta_0 + x - \gamma')(\beta_0 - \gamma')(1 + \mu\beta_0)}{(\mu\beta_0 + \mu x + 1)(\beta_0 - \gamma')(1 + \mu\beta_0)}}$$

$$f = \frac{1}{2RC \ln\left\{\left[\frac{\mu(\beta_0 - \gamma')}{(1 + \mu\beta_0)}\right]\left[\frac{(\beta_0 + x - \gamma')(1 + \mu\beta_0)}{(1 + \mu x + \mu\beta_0)(\beta_0 - \gamma')}\right]\right\}}$$

$$f = \frac{1}{2RC \ln\left\{\left[\frac{\frac{\mu}{(1 + \mu\beta_0)}}{\frac{1}{(\beta_0 - \gamma')}}\right]\left[\frac{\frac{(\beta_0 + x - \gamma')}{(\beta_0 - \gamma')}}{\frac{(1 + \mu x + \mu\beta_0)}{(1 + \mu\beta_0)}}\right]\right\}}$$

now let $a = \frac{1}{(\beta_0 - \gamma')}$ and let $b = \frac{\mu}{(1 + \mu\beta_0)}$

$$f = \frac{1}{2RC \ln\left\{\left(\frac{b}{a}\right)\left[\frac{\frac{(\beta_0 - \gamma')}{(\beta_0 - \gamma')} + \frac{x}{(\beta_0 - \gamma')}}{\frac{(1 + \mu\beta_0)}{(1 + \mu\beta_0)} + \frac{\mu x}{(1 + \mu\beta_0)}}\right]\right\}}$$

$$f = \frac{1}{2RC \ln\left[\left(\frac{b}{a}\right)\frac{(1 + ax)}{(1 + bx)}\right]}$$

$$f = \frac{1}{2RC\left[\ln\left(\frac{b}{a}\right) + \ln\frac{(1 + ax)}{(1 + bx)}\right]} \tag{7}$$

Using the power series for $\ln(1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \cdots\cdots$,
the second logarithmic expression can be expanded as follows:

$$\ln(1 + ax) = ax - \frac{a^2x^2}{2} + \frac{a^3x^3}{3} - \frac{a^4x^4}{4} + \cdots\cdots\cdots$$

$$\ln(1 + bx) = bx - \frac{b^2x^2}{2} + \frac{b^3x^3}{3} - \frac{b^4x^4}{4} + \cdots\cdots\cdots$$

$$\ln\frac{(1 + ax)}{(1 + bx)} = \ln(1 + ax) - \ln(1 + bx)$$

$$\ln\frac{(1 + ax)}{(1 + bx)} = (a-b)x - \frac{(a^2 - b^2)x^2}{2} + \frac{(a^3 - b^3)x^3}{3} - \frac{(a^4 - b^4)x^4}{4} + \frac{(a^5 - b^5)x^5}{5} \cdots\cdots\cdots$$

$$\ln\frac{(1 + ax)}{(1 + bx)} = (a-b)x\left[1 - \frac{(a + b)x}{2} + \frac{(a^2 + ab + b^2)x^2}{3} - \frac{(a^3 + a^2b + ab^2 + b^3)x^3}{4} + \cdots\cdots\cdots\right]$$

If a is not too different from b,

$$\frac{a^2 + ab + b^2}{3} \approx \left(\frac{a + b}{2}\right)^2$$

and, in general,

$$\frac{a^n + a^{n-1}b + a^{n-2}b^2 + \cdots + b^n}{n + 1} \approx \left(\frac{a + b}{2}\right)^n$$

Therefore, an approximation can be made with a new series:

$$\ln\frac{(1 + ax)}{(1 + bx)} \approx (a-b)x\left[1 - \left(\frac{a + b}{2}\right)x + \left(\frac{a + b}{2}\right)^2x^2 - \left(\frac{a + b}{2}\right)^3x^3 + \cdots\right]$$

or; $$\ln\frac{(1 + ax)}{(1 + bx)} \quad (a-b)x\left[\frac{1}{1 + \left(\frac{a + b}{2}\right)x}\right] \tag{8}$$

Now equation 7 can be rewritten:

$$f \approx \frac{1}{2RC\left[\ln\left(\frac{b}{a}\right) + \frac{(a - b)x}{1 + \frac{(a + b)x}{2}}\right]}$$

$$f \approx \frac{1 + \frac{(a - b)}{2}x}{2RC\left[\left(1 + \left(\frac{a + b}{2}\right)x\right)\ln\left(\frac{b}{a}\right) + (a - b)x\right]}$$

$$f \approx \frac{1 + \frac{(a-b)}{2} x}{2 R C \left\{ \ln\left(\frac{b}{a}\right) + x\left[\frac{(a+b)}{2} \ln\left(\frac{b}{a}\right) + (a-b)\right]\right\}} \qquad (9)$$

If $\frac{(a+b)}{2} \ln \frac{b}{a} = (b - a)$, the denominator of equation 9 is constant and the frequency becomes a linear function of the grid return voltage. It is possible to adjust the circuit parameters so this condition prevails.[5] Under these conditions the frequency equation can be rewritten:

$$f \approx \frac{1 + \frac{(a+b)}{2} x}{2 R C \ln \frac{b}{a}} \qquad (10)$$

Substituting $x = \beta - \beta_0$ in equation 10:

$$f \approx \frac{1 + \frac{(a+b)}{2}(\beta - \beta_0)}{2 R C \ln \frac{b}{a}}$$

$$f \approx \frac{1 - \frac{(a+b)}{2}\beta_0}{2 R C \ln \frac{b}{a}} + \frac{(a+b)\beta}{4 R C \ln \frac{b}{a}} \qquad (11)$$

where R = grid-return resistance, C = effective circuit capacitance, $\beta_0 = \frac{E_{co}}{E_{bb}}$ = design-center grid-return voltage, $\beta = \frac{E_c}{E_{bb}}$ = grid-return voltage, $a = \frac{1}{(\beta_0 - \gamma)}$, $b = \frac{\mu}{1 + \mu\beta_0}$, and $\gamma = \frac{R_k - R_1}{R_1 + R_k + r_p}$.

For the circuit of figure 19, the above values are: $R_g = 1 \cdot 10^6$, $C = 730 \cdot 10^{-12}$, $\beta_0 = \frac{14.5}{12} = 1.208$, $a = \frac{1}{1.208 + 0.8} = 0.499$, $\gamma = \frac{1000 - 33{,}000}{33{,}000 + 1000 + 6000} = -0.8$, and $b = \frac{4}{1 + 4(1.208)} = 0.686$.

Substituting these numerical values, and letting $\beta = \beta_0$:

$$f \approx \frac{1 - (0.592)(1.208)}{2(730)(10^{-6})(0.318)} + \frac{(1.185)(1.208)}{4(730)(10^{-6})(0.318)}$$

$$f \approx 593 \text{ cps} + 1540 \text{ cps}$$

$$f \approx 2133 \text{ cycles per second.}$$

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5. Ibid.

CHAPTER V

PULSE TIME CALCULATIONS

The operation of the monostable multivibrator is somewhat similar to that of the astable multivibrator discussed in Chapter IV. The main difference is that only the grid of one tube is coupled to the plate of the other tube. This means that the circuit is not free-running, but has a stable operating condition with one tube conducting and the other tube cutoff.

The circuit used for the pulse width modulator, redrawn in Figure 10, will be used to demonstrate the methods of calculating the pulse duration time and the linearity of the system. The resistors in

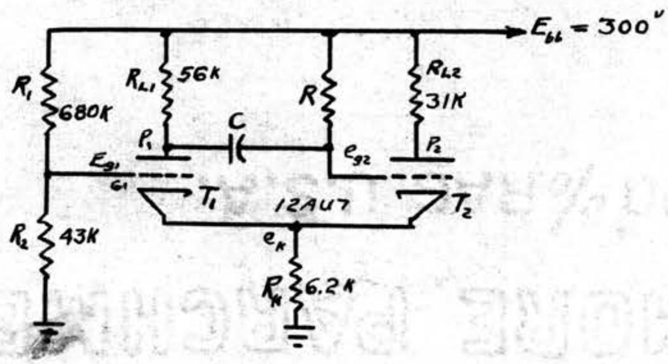

Figure 10. Monostable Multivibrator

the circuit, R_1, R_2, R_{L1}, R_{L2}, and R_k, were chosen to give practical operating conditions as determined by the tube characteristics in a tube manual.

The normal operating condition is for tube T_2 to be conducting while tube T_1 is biased to cutoff. From the tube manual the following approximate parameters were determined: r_p = 7000 ohms, μ = 16. The operating current of tube T_2 can be obtained as follows:

$$I_{02} = \frac{E_{bb}}{R_{L2} + R_k + r_p} = \frac{300}{31,000 + 6200 + 7000} = 6.8 \text{ mamp.} \quad (1)$$

$$E_{g2} = R_k I_{02} = (6.2)(10^3)(6.8)(10^{-3}) = 42 \text{ volts} \quad (2)$$

$$E_{g1} = \frac{R_2}{R_1 + R_2} E_{bb} = \frac{43}{723} 300 = 17.8 \text{ volts} \quad (3)$$

The cathode voltage, e_{k1}, will be practically the same as the grid voltage during the conducting period of tube T_1; therefore, to determine the operating current, I_{01}, of T_1, the following equation may be used:

$$I_{01} = \frac{e_{k1}}{R_k} = \frac{17.8}{6,200} = 2.87 \cdot 10^{-3} \text{ amp.} \quad (4)$$

The voltage drop across R_{L1}, which helps determine the maximum negative voltage of e_{g2}, is determined as shown below:

$$E_{p1} = R_{L1} I_{01} = 56 \cdot 10^3 \cdot 2.87 \cdot 10^{-3} = 161 \text{ volts} \quad (5)$$

Now the pulse duration time may be determined in a manner similar to that used for the free-running multivibrator. The minimum voltage of the grid of T_2 is equal to its voltage during conduction of tube T_2 minus the voltage drop across the load resistor of T_1 when it is conducting. This minimum voltage is expressed below:

$$E_{g2m} = E_{g2} - E_{p1} = 42 - 162 = -120 \text{ volts} \quad (6)$$

The cutoff voltage of T_2, which is the voltage the grid must reach to start conduction, is:

$$E_{co2} = -\frac{E_{bb}}{\mu} = -\frac{300}{16} = -18.8 \text{ volts} \quad (7)$$

The formula which expresses the voltage on the grid of T_2 as it rises exponentially with time from its maximum negative value, taken at the time t = 0, is:

$$e_{g2} = E_{bb} - (E_{bb} - E_{g1})\varepsilon^{-\frac{t}{RC}} \quad (8)$$

The time required for the grid to reach cutoff may be determined by solving equation 8 with the cutoff voltage used for e_{g2} :

$$E_{co2} = E_{bb} - (E_{bb} - E_{gm})\varepsilon^{-\frac{t}{RC}}$$

Substituting values from equations 6 and 7

$$-18.8 = 300 - (300 + 120)\varepsilon^{-\frac{t}{RC}}$$

$$\varepsilon^{-\frac{t}{RC}} = 0.759$$

$$\frac{t}{RC} = 0.276$$

To establish a pulse duration time of 150 microseconds, let the value of $0.276\,RC = 150 \cdot 10^{-6}$. If C is chosen, R may be calculated as shown below:

Let C = 100mmfd.

$$R = \frac{150 \cdot 10^{-6}}{0.276 \cdot 100 \cdot 10^{-12}} = 5.4 \cdot 10^{6} \text{ ohms}$$

When the circuit was actually built and tested, it was found that a value of five megohms for R gave a pulse duration time of 150 microseconds. Using this value of R, the calculated value of C would be 108 mmfd. This value is within the manufacturers tolerances for a 100 mmfd. capacitor.

The pulse duration time, or delay, is quite accurately linearly related to the grid voltage , E_{g1}. The linearity results from the fact that I_1 is linearly related to the voltage E_{g1}, and that the duration time, T, of the pulse is linearly proportional to I_1.[6] To show that the pulse duration time is linear with I_1, one may proceed

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6. Jacob Millman, Herbert Taub, Pulse and Digital Circuits, Mc Graw-Hill Book Co., Inc., New York, 1956, pp 187-194

as shown in the following pages. This explanation is taken from the literature.[7]

The bias voltage, E_{g1}, must be less than $I_{02}R_k$ by at least the cutoff voltage of T_1, or E_{co1}. The maximum value of E_{g1} can therefore be expressed:

$$E_{g1max} = I_2 R_k + E_{co1} \qquad (9)$$

Immediately after triggering, P_1 and G_2 drop by the amount $I_1 R_{L1}$ and the cathode changes from $I_2 R_k$ to $I_1 R_k$.

The current, I_1, must be large enough to drive T_2 below cutoff. This minimum current, I_{min}, can be calculated as follows:

$$E_{g2} = I_2 R_k - I_{1min} R_{L1} \qquad (10)$$

$$E_k = I_{1min} R_k$$

Since E_{g2} must be less than E_k by the cutoff voltage, E_{co2},

$$E_{g2} - E_k = E_{co2}$$

$$\text{or} \quad I_2R_k - I_{1min}R_{L1} - I_{1min}R_k = E_{co2}$$

$$\text{so} \quad I_{1min} = \frac{I_2R_k - E_{co2}}{R_{L1} + R_k} \qquad (11)$$

The value of E_{g1min} must not be less than a value which allows a tube current of I_{min}.

The equation for the exponentially rising portion of E_{g2} is

$$e_g = E_{bb} - \left[E_{bb} - (I_2R_k - I_1R_{L1})\right] \varepsilon^{-\frac{t}{RC}} \qquad (12)$$

when $t = T \quad e_g = I_1R_k + E_{co2}$

$$I_1R_k + E_{co2} = E_{bb} - \left[E_{bb} - (I_2R_k - I_1R_{L1})\right] \varepsilon^{-\frac{T}{RC}}$$

$$\varepsilon^{-\frac{T}{RC}} = -\frac{I_1R_k + E_{co2} - E_{bb}}{E_{bb} - I_2R_k + I_1R_{L1}}$$

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7. Ibid.

$$\frac{T}{R\,C} = \ln \frac{E_{bb} + I_1R_{L1} - I_2R_k}{E_{bb} - E_{co2} - I_1R_k} \tag{13}$$

At this point the variable, $I_{10} = I_1 - I_{min}$, may be introduced, where I_{10} is the departure of the tube current from the current corresponding to E_{g1min}. Also, let $E' = E_{bb} + I_{min}R_{L1} - I_2R_k$ (14)

From (11) $\quad I_{1min}R_{L1} = I_2R_k - I_{1min}R_k - E_{co2}$

Substituting in (14):

$$E' = E_{bb} - I_{1min}R_k - E_{co2} \tag{15}$$

Rewriting equation (13):

$$\frac{T}{R\,C} = \ln \frac{E_{bb} + (I_{10} + I_{1min})R_{L1} - I_2R_k}{E_{bb} - E_{co2} - (I_{10} + I_{1min})R_k}$$

$$\frac{T}{R\,C} = \ln \frac{E' + I_{10}R_{L1}}{E' - I_{10}R_k}$$

$$\frac{T}{R\,C} = \ln \frac{1 + \frac{I_{10}R_{L1}}{E'}}{1 - \frac{I_{10}R_k}{E'}} \tag{16}$$

Making use of the expansion $\ln(1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \cdots\cdots$

$$\ln\left[1 + \frac{I_{10}R_{L1}}{E'}\right] = \frac{I_{10}R_{L1}}{E'} - \frac{1}{2}\left(\frac{I_{10}R_{L1}}{E'}\right)^2 + \frac{1}{3}\left(\frac{I_{10}R_{L1}}{E'}\right)^3 \quad - \cdots\cdots$$

$$\ln\left[1 - \frac{I_{10}R_k}{E'}\right] = -\frac{I_{10}R_k}{E'} - \frac{1}{2}\left(\frac{I_{10}R_k}{E'}\right)^2 - \frac{1}{3}\left(\frac{I_{10}R_k}{E'}\right)^3 \quad - \cdots\cdots$$

$$\frac{T}{R\,C} = \ln\left[1 + \frac{I_{10}R_{L1}}{E'}\right] - \ln\left[1 - \frac{I_{10}R_k}{E'}\right]$$

$$\frac{T}{R\,C} = \frac{I_{10}(R_{L1} + R_k)}{E'} - \frac{1}{2}\left(\frac{I_{10}}{E'}\right)^2(R_{L1}^2 - R_k^2) + \frac{1}{3}\left(\frac{I_{10}}{E'}\right)^3(R_{L1}^3 + R_k^3) - \frac{1}{4}\left(\frac{I_{10}}{E'}\right)^4(R_{L1}^4 - R_k^4) + \cdots\cdots$$

$$\frac{T}{R\,C} = \frac{I_{10}}{E'}(R_{L1} + R_k)\left[1 - \frac{I_{10}}{2E'}(R_{L1} - R_k) + \frac{1}{3}\left(\frac{I_{10}}{E'}\right)^2(R_{L1}^2 - R_{L1}R_k + R_k^2) - \cdots\cdots\right] \tag{17}$$

If $I_{10}R_{L1}$ and $I_{10}R_k$ are both small in comparison to E', then

$$\frac{T}{R\,C} \approx \frac{I_{10}}{E'}(R_{L1} + R_k)\left[1 - \frac{I_{10}}{2E'}(R_{L1} - R_k)\right] \qquad (18)$$

which represents the first two terms of equation 17. From equation 18 it can be seen that linearity may be expected as long as the quantity $I_{10}(R_{L1} - R_k) \ll 2\,E'$. If $R_{L1} = R_k$ there would be perfect linearity, if equation 18 were used. This just means that more terms of equation 17 would be needed to determine the linearity.

According to Millman and Taub, it has been determined experimentally that it is possible to adjust the cathode coupled multivibrator to provide a linearity error of one per cent.

CHAPTER VI

TESTING THE CIRCUITS

The circuits which have been described in the previous chapters were built and preliminary tests were performed. The circuit component values which were used are listed in tables I, II, and III. The results of the testing indicate that the original requirements have been fulfilled in most respects. The one requirement not completely satisfied was that of crosstalk, as will be discussed in following paragraphs.

Figure 11 shows amplitude vs. frequency curves for both channels of the system. It can be seen that the system is essentially flat beyond the limits of 10 and 100 cycles per second. These measurements were made by feeding an oscillator signal through a microvolter, to obtain a measured input, to the modulators. The demodulator outputs were measured with a Tektronix type 535 oscilloscope.

To measure the signal to noise ratio, the same test instruments mentioned in the previous paragraph were used. The peak signal was measured by increasing the input signal until the output signal, which was being monitored with the oscilloscope, appeared distorted, then reducing the signal just enough to remove the apparent distortion. The peak noise was measured by grounding the input and observing the output signal on the oscilloscope. The largest amplitude transient seen in several moments of observation was used as the peak noise signal. Actually no large transients were noticed, but only the normal ripple

TABLE I

RESISTOR SIZES

Resistor	Size
R_1	.5 Meg
R_2	.24 Meg
R_3	3 K
R_4	8.2 Meg
R_5	1 Meg
R_6	1 Meg
R_7	1 Meg
R_8	1 K
R_9	1 K
R_{10}	33 K
R_{11}	33 K
R_{12}	.51 Meg
R_{13}	30 K
R_{14}	200 Ohm
R_{15}	.1 Meg
R_{16}	.22 Meg
R_{17}	20 K
R_{18}	.68 Meg
R_{19}	43 K
R_{20}	2 Meg
R_{21}	56 K
R_{22}	5.1 Meg
R_{23}	31 K
R_{24}	6.2 K
R_{25}	.51 Meg
R_{26}	.24 Meg
R_{27}	3 K
R_{30}	1 Meg
R_{31}	1.8 K
R_{32}	8.2 K
R_{33}	10 K
R_{34}	51 K
R_{35}	110 K
R_{36}	20 K
R_{37}	180 K
R_{38}	10 K
R_{39}	51 K
R_{40}	1 Meg
R_{41}	3.1 K
R_{42}	15 K
R_{43}	.51 Meg
R_{44}	.68 Meg
R_{45}	.1 Meg
R_{46}	6.2 K
R_{47}	31 K
R_{48}	5.1 Meg
R_{49}	51 K
R_{50}	.18 Meg
R_{51}	15 K
R_{52}	6.2 K
R_{53}	.1 Meg
R_{54}	1 Meg
R_{55}	1 Meg
R_{59}	10 K
R_{56}	1 Meg
R_{57}	20 K
R_{58}	1 Meg
R_{60}	51 K
R_{61}	.51 Meg
R_{62}	51 K
R_{63}	.1 Meg
R_{64}	6.2 K
R_{65}	.18 Meg
R_{66}	10 K
R_{67}	51 K
R_{68}	1 Meg
R_{69}	15 K
R_{70}	3 K
R_{71}	.1 Meg
R_{72}	.5 Meg
R_{73}	.24 Meg
R_{74}	3 K
R_{75}	1 Meg
R_{76}	.51 Meg
R_{77}	51 K
R_{78}	240 K
R_{79}	3 K
R_{80}	1 Meg

TABLE II

CAPACITOR SIZES

Capacitor	Size	Capacitor	Size	Capacitor	Size
C_1	.1 mfd	C_{13}	.01 mfd	C_{25}	.02 mfd
C_2	50 mfd	C_{14}	400 mmfd	C_{26}	.002 mfd
C_3	.1 mfd	C_{15}	1 mfd	C_{27}	.01 mfd
C_4	730 mmfd	C_{16}	.002 mfd	C_{28}	30 mmfd
C_5	730 mmfd	C_{17}	.002 mfd	C_{29}	.1 mfd
C_6	.01 mfd	C_{18}	200 mmfd	C_{30}	.1 mfd
C_7	100 mmfd	C_{19}	400 mmfd	C_{31}	50 mfd
C_8	100 mmfd	C_{20}	.01 mfd	C_{32}	.002 mfd
C_9	.01 mfd	C_{21}	350 mmfd	C_{33}	.02 mfd
C_{10}	.1 mfd	C_{22}	.001 mfd	C_{34}	.1 mfd
C_{11}	500 mmfd	C_{23}	100 mmfd	C_{35}	50 mfd
C_{12}	500 mmfd	C_{24}	.1 mfd		

TABLE III

TUBES

Tubes	Type
V101, V102	12AX7
V103, V104	12AU7
V105, V106	12AT7
V107, V108	12AU7
V109, V110	12AU7
V111, V112	12AU7
V113, V122	12AU7
V114, V115	12AU7
V117, V118	12AU7
V116, V121	12AU7
V119, V120	12AX7
V123, V124	12AU7
V125, V126	12AX7

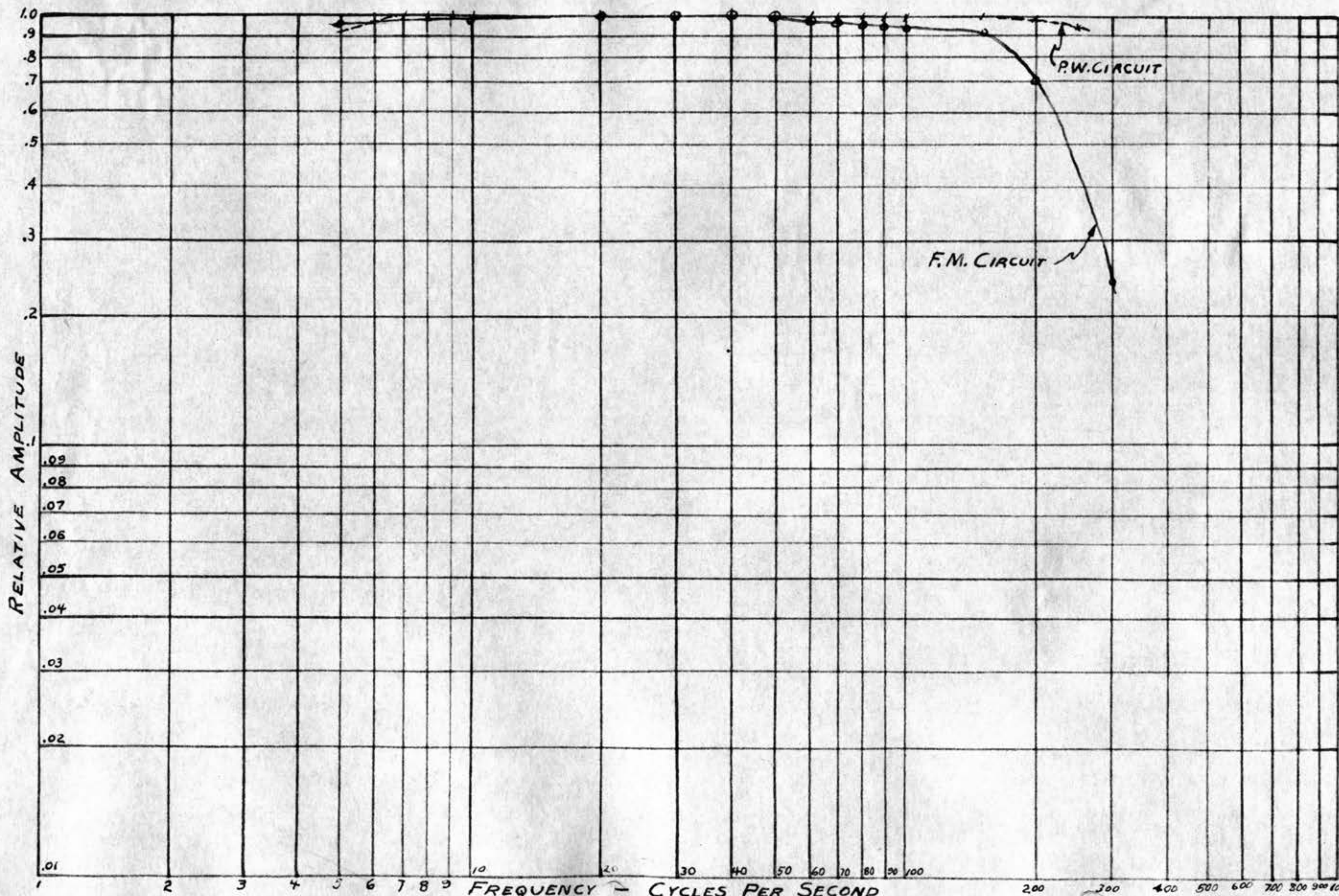


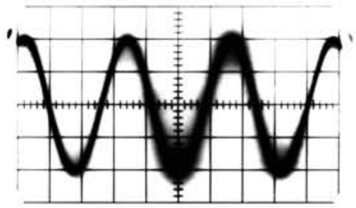
Figure 11. Frequency Response

and jitter. The measurements of peak, undistorted signal and peak noise, with no input signal, gave a signal to noise ratio of 300:1, or about 50 db.

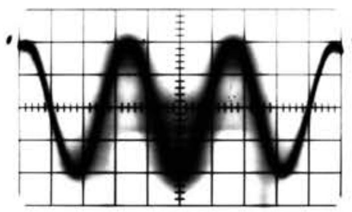
The crosstalk, or interaction of one channel on the other, was the one thing which caused the most trouble. The measurements to determine the crosstalk were made by feeding the oscillator signal to only one input, then using the oscilloscope to monitor the output signal associated with the other input. The interaction of the pulse duration time on the F. M. channel was negligible and at least as good as the signal to noise ratio. The interaction of the pulse repetition rate on the pulse width channel was troublesome. The final circuit, as shown in Figures 4 and 7, has a ratio of 100:1 of pulse width information signal to the crosstalk from the F. M. channel. Although this does not meet the original specifications, for many purposes it would be sufficient. With further refinements in the bootstrap amplifier circuit, this interference could probably be reduced even more.

Visual observations of the operation of the various parts of the circuit were recorded with the aid of the cathode ray oscilloscope and a Polaroid camera . Figures 12 through 21 are examples of the waveforms at various points of the circuit.

In Figure 12 the input signal to the F. M. modulator is shown at the top. The waveform at the bottom of the same figure is the final output of the F. M. demodulator. Figure 13 shows the waveforms at the plate of tube V103, which is the astable multivibrator in the F. M. circuit. The top waveform is without modulation while the bottom waveform shows the effect of modulation. It is obvious that both the leading and trailing edges of the pulses are varying. The trigger

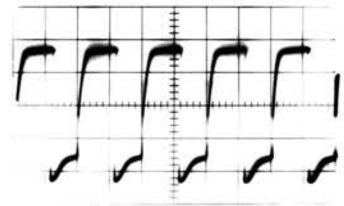


Input

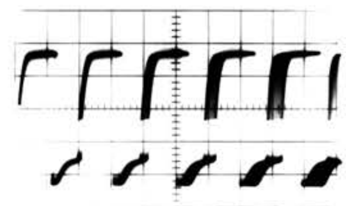


Output

Figure 12.
F. M. Circuit
Waveforms

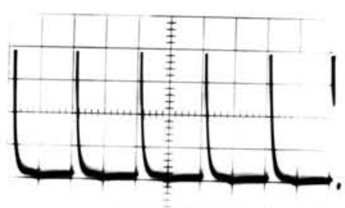


Unmodulated

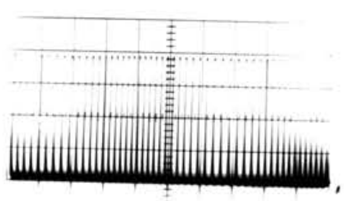


Modulated

Figure 13. Astable
Multivibrator Waveforms

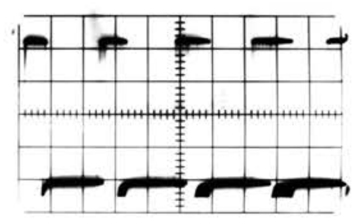


Unmodulated

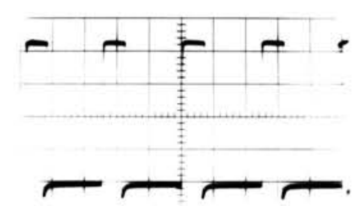


Modulated

Figure 14. F. M.
Trigger Pulses



F. M. Modulated



Unmodulated

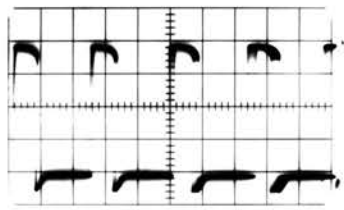
Figure 15. Modulator Output

spikes, as applied to the grid of tube V106, are shown in Figure 14. The top picture shows a few spikes without modulation while the bottom picture illustrates more cycles at the same point with a modulating signal applied. The output of the modulator showing F. M. modulation only and no modulation is shown in Figure 15. Once again the effect of varying repetition rate is indicated by the movement of both the leading and trailing edges of the pulses. Waveforms in the frequency modulation demodulator are shown in Figure 16. The top pulses show the output of the monostable multivibrator at the plate of tube V112. The triangular pulses were obtained in the filter at the junction of R_{43}, L_1, and C_{16}.

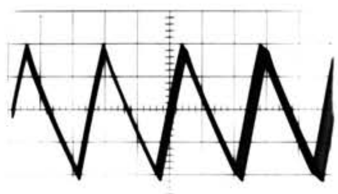
The top half of Figure 17 shows the input waveform to the pulse width modulator. The bottom half shows the final output of the pulse width demodulator. The output of the modulator is shown again in figure 18. The unmodulated pulses are compared with pulses which have been modulated by the pulse width circuit. Only the trailing edges of the pulses show any indications of modulation.

Some of the waveforms in the pulse width demodulator are shown in Figures 19 and 20. The output of the bootstrap amplifier, at the cathode of tube V118, is shown in Figure 19. The top shows the unmodulated sweep with the sampling pulses showing up slightly more than halfway up the slope. The bottom picture shows the effect of pulse width modulation on the sampling pulses. The stairstep voltage change of the capacitor, C_{22}, is shown in the top part of Figure 20. The bottom half shows the waveform on C_{23}.

The final picture, Figure 21, shows the simultaneous outputs of the frequency modulation demodulator and the pulse width demodulator.

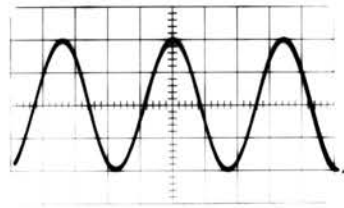


Multivibrator Pulses

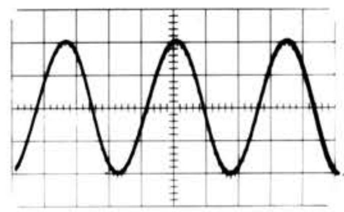


Signal in Filter

Figure 16. F. M. Demodulator Waveforms

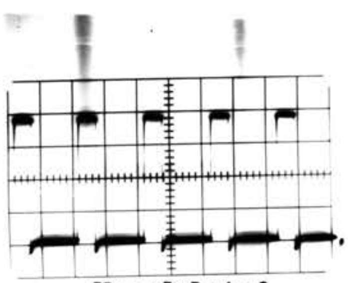


Input

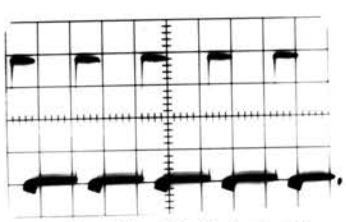


Output

Figure 17. P. W. Circuit Waveforms

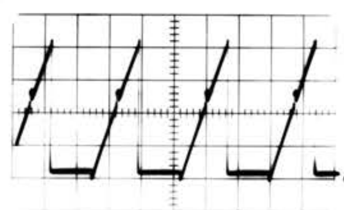


Unmodulated



P. W. Modulated

Figure 18. Modulator Output

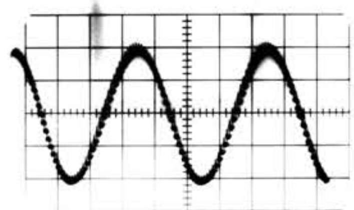


Unmodulated

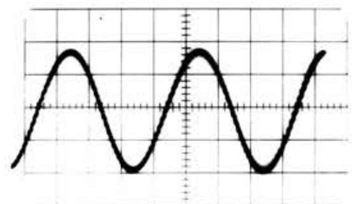
Modulated

Figure 19. Bootstrap Amplifier Output

The information signal modulating the repetion rate of the carrier was a 90 cycle per second sine wave while the signal modulating the pulse duration time of the carrier was a 45 cycle per second sine wave.



Signal on C_{22}



Signal on C_{23}

Figure 20. P. W. Demodulator Waveforms

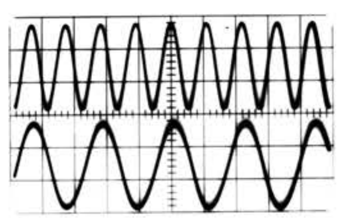


Figure 21. Output Signals of Both Demodulators

CHAPTER VII

SUMMARY AND CONCLUSIONS

The object of the project which has been discussed in the preceeding chapters was to design, build, and test a circuit which would be useful in extending the capacity of a magnetic tape recording system which is used for petroleum seismic exploration.

The method proposed was to combine two common forms of modulation to introduce two separate information signals to a common carrier signal and, as a result, provide a system capable of doubling the number of signals which could be recorded on a given tape recorder. The two forms of modulation used were pulse width modulation and frequency modulation. One of the information signals was used to vary the repetition rate, or frequency, of a pulse wave carrier while the other information signal was used to vary the pulse duration time, or pulse width.

The circuits were built and tests were made to determine the frequency response, signal to noise ratio, and the crosstalk, or intermodulation, of the system. The results of the tests indicate that the circuits fulfilled the specifications to a large extent and would be useful in most seismic recording. The fact that there was some crosstalk in the system would limit its use in some areas; however, it is likely that further development, especially in the pulse width demodulator circuitry, would enable the system to be useful in all areas.

More development work is in order before the circuits described could be put into routine operation. Sysem tests will have to be made combining the modulating and demodulating circuits with conventional amplifying, filtering, and automatic gain controlling circuits.

The system described in this paper would double the capacity of the magnetic tape recorders which are now in use. Adoption of the system proposed would double the number of information signals which could be recorded on each tape with very little increase in recording equipment.

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