AN ANALYSIS OF
A CRYSTAL-DRIVEN AMPLIFYING DETECTOR

By

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PREFACE

The problem of demodulating amplitude-modulated radio frequencies has been studied by a large number of outstanding electrical engineers. Many papers have been written on the analysis of various types of a-m detector circuits. It has been shown by these numerous analyses that the best type of a-m detector for use in the ordinary a-m receiver is the linear diode detector. Mr. Robert Ledbetter has spent many years working with audio frequency equipment. Recently he constructed a receiver in which he employed a new type detector circuit and obtained very satisfactory results. It was felt that an interesting study could be made by analyzing this new circuit, determining its merits, and comparing it with the popular linear diode detector circuit.

ACKNOWLEDGMENT

The author wishes to express his sincere appreciation to Professor A. L. Betts for his guidance and interest in the preparation of this thesis. He also wishes to extend thanks to Professor H. T. Fristoe for his help in starting this project, and to Mr. Robert Ledbetter who furnished the original idea.

The author also wishes to acknowledge the assistance and encouragment given him by his wife, Margie, who helped greatly in the typing and preparation of this manuscript.

TABLE OF CONTENTS

CHAPTER

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Modulation is defined in the 1938 Standards Report of the Institute of Radio Engineers as "the process of producing a wave some characteristic of which varies as a function of the instantaneous value of another wave, called the modulating wave."[1]

The most outstanding applications of modulation are in the field of communication, where it is used in the transmission of voice, music, pictures, and other forms of information by means of radio and wire. In the application to radio, the information-carrying frequencies are modulated or superimposed on higher radio frequencies which are capable of establishing radiating fields to carry the information over great distances without the aid of interconnecting wires. The modulating frequencies are in themselves too low to produce a substantial radiating field, so that only through the medium of modulation is radio communication possible. This communication may take the form of telegraphy, telephony, facsimile, or television, all of which utilize the same fundamental principles of modulation and demodulation.[2]

There are four basic types of modulation used in radio communications. They are amplitude modulation, frequency modulation, phase modulation, and pulse time modulation. This investigation will concern only amplitude-modulated waves. The Standards Report of the Institute of Radio Engineers defines an amplitude-modulated wave as "one whose envelope contains a component similar to the wave form of the signal to be transmitted." If the

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[1] Eastman, Austin V., Fundamentals of Vacuum Tubes, p. 508.

[2] Ibid., p. 510.

wave shape of the envelope is exactly like that of the signal, modulation is said to be linear and no distortion is present.[3]

After the transmitted carrier with its superimposed modulating frequency has reached some remote point, the original signal must be removed from the carrier before it can be used. The process by which this is accomplished is known as demodulation or, especially with carrier waves of radio frequency, detection, and the vacuum tubes and associated circuits used in this process are known as demodulators or detectors.

Demodulation is defined by the Institute of Radio Engineers in their Standards Report as "the process of modulation carried out in such a manner as to recover the original signal." As implied in this definition, the process of modulation and demodulation are very similar, the difference usually lies primarily in the type of output circuit selected to utilize the products obtained.[4]

There are many different types of detectors used in modern a-m receivers. These include diode detectors, plate detectors (also called bias detectors), grid-leak detectors, infinite impedance detectors, regenerative detectors, and crystal detectors. Of these, the three basic types used for the detection of amplitude-modulated waves are the diode detector, the plate detector, and the grid-leak detector. There are advantages and disadvantages that accompany each of the above. For example, the diode detector has the advantage of a source of avc voltage, which is a negative signal proportional to the signal strength that is fed from the detector stage back to preceding amplifier stages to maintain a constant signal level. The plate detector has

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[3] Ibid., pp. 510-511.

[4] Ibid., p. 563.

the advantage over the diode detector of greater sensitivity since it amplifies the demodulated signal, but requires a separate tube to provide an avc voltage. The grid-leak detector also produces an amplified demodulated signal, but has the disadvantage that grid current flows in the input circuit.

It is entirely possible that there are other methods of demodulating an a-m signal. It is the purpose of this paper to investigate and analyze the operation of a non-conventional type of detector circuit. Since the linear diode detector is by far the most popular in commercial radio, it should prove interesting to compare the operation of this new type detector with the linear diode detector.

CHAPTER II

REVIEW OF LITERATURE

A. The Non-Linear Element

Rectification may be defined as an operation on an a-c voltage to produce an uni-directional component. The uni-directional component arises from the fact that the average resistance to current flow is less in one direction than in the other. In addition to the d-c component in the rectifier output, there are also present harmonics of the input signal which arise because of the non-linear character of the rectifying element. The relative amplitudes of the harmonics depend on the shape of the current-voltage characteristic curve in the operating region. The magnitude of the d-c component also depends on the shape of the characteristic. For example, a non-linear element having the characteristic curve of Figure 1-a will have no d-c component in the output if operated at zero bias, but if a d-c bias voltage is applied so that the operating point is at A, the application of a small a-c signal will result in a net increase in the direct current over that produced by the bias alone. This occurs because the average current will be greater for the positive swings than for the negative ones.

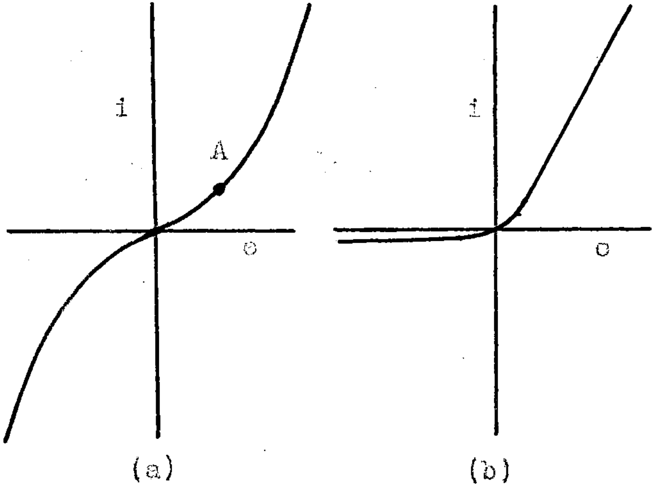

Figure 1

Non-Linear Element
Characteristics
(a) A symmetrical characteristic
(b) A characteristic useful for detection

Rectifiers that are useful for detection purposes have characteristics similar to that shown in Figure 1-b. The shape of the characteristic will, of course, depend on the physical nature of the rectifier. In general, the important features are a high back resistance and a relatively low forward resistance.[1]

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[1] Torrey, H. C. and Whitmer, Charles C., Crystal Rectifiers, p. 1.

B. Detection

In the use of the rectifier for detection there are two classifications that are of particular interest: (1) linear and (2) square-law detection.

Linear Detection - In linear detection, the rectifier functions essentially as a switch. An ideal rectifier characteristic is shown in Figure 2. It is well known that when a sinusoidal wave is impressed on the ideal rectifier the average current will be proportional to the amplitude of the input wave. This is true because the resistance in the back direction is infinite and in the forward direction it is low and constant. The voltage across the rectifier load will then be composed of a d-c component proportional to the amplitude of the input frequency and its even harmonics.

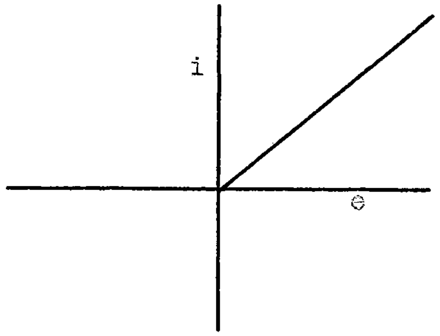

Figure 2
Ideal Rectifier
Characteristic

Most rectifiers will approximate this ideal performance if the input signal is large enough to make the region of curvature near the origin small compared with the substantially straight part of the characteristic over which the voltage varies. Furthermore, the load resistance is usually chosen large compared with the rectifier resistance so that the effect on the output voltage of variation of the forward resistance of the rectifier is small.

The efficiency of rectification is defined as the ratio of the d-c voltage across the output load resistance to the peak amplitude of the input signal. It depends on the ratio of load resistance to the internal resisance of the rectifier and the amplitude of the input signal.

In the detection of amplitude-modulated waves in radio reception a load consisting of a parallel RC combination is commonly used. (See Figure 3 which shows a vacuum tube diode as the rectifier.) With proper choice of R and C the output voltage will, to a very close approximation, very like the envelope of the amplitude-modulated wave. Under these conditions, the rectification efficiency of vacuum tube diodes is normally about 70 to 90 per cent.[2]

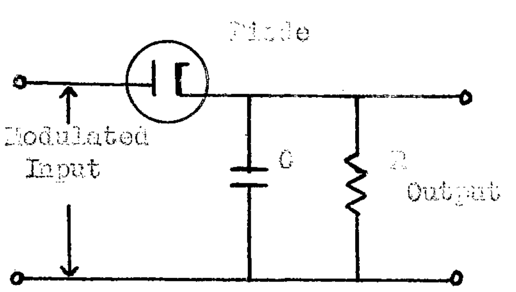

Figure 3

Simple Diode Detector

Square-Law Detection - The term square-law is applied to a detector in which the d-c, or rectified, output is proportional to the square of the amplitude of the input. This has also been called detection by curvature of the current-voltage characteristics.[3] It is obvious then that such a response depends on the nonlinearity of the characteristics at the operating point. Over a limited range the current-voltage characteristics of a rectifier can be represented by a Taylor expansion terminating in the squared term

$$i = f(e) = f(e_o) + \frac{df}{de}\delta e + \frac{1}{2}\frac{d^2f}{de^2}(\delta e)^2 \tag{2-1}$$

where e_o is the bias voltage determining the operating point, and δe is the small input signal voltage. The derivatives are evaluated at the operating point e_o. Any rectifier will, therefore, function as a square-law rectifier where the applied signal is sufficiently small, provided the second deriva-

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[2] Ibid., pp. 2-3.

[3] Reich, H. J., Theory and Application of Electron Tubes, p. 301.

tive of the characteristic does not vanish at the operating point.[4]

A rigorous analysis of square-law detection will not be attempted here. However, a thorough analysis may be found in a number of standard textbooks on vacuum tube circuits.[5]

The analysis may be summarized briefly as follows. Considering an input signal of sinusoidal waveform, the output will contain, in addition to the frequency of the signal, d-c and second-harmonic components with amplitudes proportional to the square of the input voltage. In general, if the excitation voltage contains two or more frequencies, the output current will contain components having these frequencies, their harmonics, the sums and differences of the impressed frequencies and their integral multiples and a steady component. The amplitude of the d-c component will be proportional to the sum of the squares of the amplitudes of the signal components. The amplitude of each second-harmonic component will be proportional to the square of the amplitude of the corresponding signal component; the amplitudes of the sum and difference frequencies will be proportional to the product of the amplitudes of the input components involved in the combination.[6]

The square-law detector is a useful device for the measurement of the power of an a-c signal because the rectified output is proportional to the square of the input amplitude.[7]

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[4] Torrey and Whitmer, Op. Cit., p. 3.

[5] Reich, Op. Cit., p. 502.

[6] Torrey and Whitmer, Op. Cit., pp. 3-4.

[7] Ibid., p. 4.

C. The Nature of the Crystal Rectifier

In the early days of the development of radio communication the crystal rectifier was almost universally used as the detector in radio receivers. A typical detector was made by soldering or clamping a small piece of the crystal in a small cup or receptacle. The rectifying contact was made with a flexible wire "cat whisker" which was held in light contact with the crystal. Good rectification was obtained only from "sensitive" spots on the crystal and frequent adjustments of the contact point were necessary for good performance.

The development of thermionic tubes made the crystal rectifier obsolete in radio receivers. From about 1925 to 1940 the crystal rectifier was used chiefly as a laboratory device for detecting and monitoring uhf power.[8]

The development of radar and other types of microwave equipment stimulated research on crystal rectifiers. Reception of microwave radar echoes requires a high gain receiver in which the limit of sensitivity is determined by the masking of the signal by the noise generated in the receiver circuits. Since vacuum tubes become increasingly noisy at increased frequency, attention was turned to the crystal rectifier as a possible substitute for use as mixers and detectors of microwave pulses. Besides the current-voltage characteristic, noise figure, conversion loss, and the r-f and i-f impedances of the rectifier are of prime importance in designing a crystal rectifier.

The research work has been concerned exclusively with silicon, boron, and germanium. Contrary to widely held opinion, the crystal rectifier has

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[8] Ibid., pp. 5-6.

been perfected to a point where, handled with reasonable care, it has remarkable endurance and stability, both mechanical and electrical. Extensive research on germanium has resulted in the development of the high-inverse-voltage rectifier and the welded contact rectifier.

Although the high-inverse-voltage crystal rectifier was developed for use as the second detector in radar receivers, its high-inverse-voltage characteristic makes it useful in applications to low frequency rectifiers. The 1N34 "diode" is rated for use at a maximum peak inverse voltage of 50 volts, a peak anode current (sine wave) of 60 ma maximum, and an average anode current of 22.5 ma.[9]

The advantages which the crystal rectifier of the high-inverse-voltage type has over the tube diode include the following:

1. No filament voltage is required; consequently, there is no need for a heater power supply and can contribute no hum.
2. There is a relatively high forward conductance.
3. The current voltage curve passes through the origin.
4. Tests indicate that the properties of crystals drift less with time when under use than do the properties of diodes.

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[9] Ibid., p. 363.

CHAPTER III

ANALYSIS OF LINEAR DIODE DETECTION

It was felt that an analysis of a linear diode detector would help in the understanding of the general problems involved in the design of detectors along with the limitations that exist as to their performance. Many authors have analyzed the linear detector. Any standard textbook on radio engineering will contain such an analysis.[1]

In the diode rectifier the direct output varies linearly with the input voltage and is nearly equal to the peak value of the input voltage over a wide range. This is the reason for the widespread use of diode detectors in radio receivers. This unique behavior is possible because the input voltage is not directly applied to the diode, but is made to furnish a direct bias, such that the only voltage causing the diode to conduct is the differential between the input and the self bias.

Figure 3 shows a simple linear diode detector. If the applied voltage is an amplitude-modulated sine wave, a properly chosen RC product will cause the condenser voltage to follow very closely the envelope magnitude of the input.

For ideal operation certain conditions must be fulfilled.

1. The time constant RC must be large enough to let C hold most of its charge during the r-f cycle. It must be small enough to allow the output voltage to follow the envelope variations.
2. The effective load impedance should be essentially the same at audio frequencies as the d-c resistance.

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[1] Terman, F. E., Radio Engineering, pp. 502-513.

3. Allowance should be made for the effect on the input circuit of the current drawn by the diode.
4. The input voltage should be large enough to provide linear operation.[2]

Figure 4-a shows the action of the condenser in eliminating the r-f variations in the output. The condenser charges to nearly the peak value of the input wave during one-half cycle, then discharges through the resistor, R, during the next half cycle producing the jagged curve. Of course, the r-f variations are greatly exaggerated and there would actually be many more cycles of the r-f frequency for each envelope cycle. For the condenser voltage to remain smaller than the envelope voltage during any period of time, Δt, the slope of the curve of condenser voltage, must be more negative than the slope of the envelope of the modulated wave.

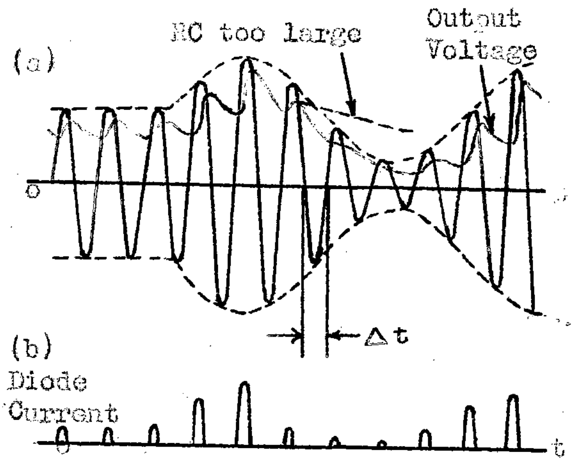

Figure 4

Waveforms in Figure 3
(a) The action of C in eliminating the r-f variations and
(b) The diode current.

A time constant that satisfies this relation is given by

$$RC \leq \frac{1}{\omega_m} \frac{\sqrt{1 - M^2}}{M} \qquad (3\text{-}1)$$

where M is the ratio of one-half the difference between the maximum and minimum amplitudes to the average amplitude of the modulated carrier and ω_m is

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[2] Arguimbau, L. B., Vacuum Tube Circuits, pp. 431-433.

the maximum angular modulating frequency the detector is designed to handle.[3] Equation 3-1 may be expressed in a different way, namely

$$(3\text{-}2) \qquad M \leqq \frac{1}{\sqrt{1 + \left(\frac{f_m}{f_o}\right)^2}} \qquad f_o = \frac{1}{2\pi RC}$$

where f_m is the maximum modulating frequency. It has been shown[4] experimentally that the amount of harmonic generation, or distortion, in the detector is not excessive for reproduction of sound if

$$(3\text{-}3) \qquad RC \leqq \frac{1}{\omega_m M} \qquad \text{or} \qquad M \leqq \frac{f_o}{f_m}\,.$$

The rectification efficiency, D, of a linear diode detector is equal to the ratio of E_{dc} to E_{ac} peak and is independent of the applied voltage. D is determined only by the ratio of the load resistance to the dynamic diode resistance.

$$(3\text{-}4) \qquad \frac{R_L}{R_D} = \frac{\pi D}{\sqrt{1 - D^2} - D\cos^{-1}D}$$

Also the effective input resistance, R_e, of the linear detector circuit is independent of the applied voltage.[5]

$$(3\text{-}5) \qquad R_e = \frac{\pi R_D}{\cos^{-1}D - D\sqrt{1 - D^2}}$$

This implies, then, that the potential developed across the load resistor will be proportional to the amplitude of the carrier envelope. Actually, this is not necessarily true.

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[3] Massachusetts Institute of Technology Staff, Applied Electronics, pp. 656-658.

[4] Terman, F. E. and Nelson, J. R., "Discussion of 'Some Notes on Grid-Circuit and Diode Rectification'", Proceedings of the Institute of Radio Engineers, XX (1932), pp. 1971-1974.

[5] Kilgour, G. E. and Glessner, J. M., "Diode Detection Analysis", Proceedings of the Institute of Radio Engineers, XI (1933), pp. 930-943.

If the rectification curves, which are Rectified Current vs DC bias potential with the peak a-c input as a variable parameter (See Figure 5) are plotted, ideally and theoretically there will be equal increments of d-c bias with equal variations in a-c input voltage. Actually, not only will the static curves not be linear, but the coupling to the next stage reduces the a-c resistance while the d-c resistance stays the same. The dynamic or a-c resistance load line will have a greater slope than the d-c or static load line. (See Figure 5). Since both load lines pass through the operating point, P, the dynamic load line reaches zero before the crest value of voltage does and consequently, the tube current will be zero before the negative peaks reach a minimum. Thus, with high modulation percentages, negative peak clipping will result. The modulation factor at which cut-off distortion will start is given by[6]

(3-6) $$M = 1 + D(A - 1)$$

where $$A = \frac{R_g}{R_L + R_g} = \frac{R_{ac}}{R_{dc}}.$$

The current in a diode consists of uni-directional pulses flowing only near the positive peaks of the input voltage. This current may be split up into a steady component, a component at the fundamental frequency and a series of components at harmonic frequencies by Fourier Analysis.

(3-7) $$i_D = i_o + i_1(\text{peak}) \sin \omega t + i_2(\text{peak}) \sin (2\omega t + \theta) + \ldots\ldots$$

The amplitude of the component at fundamental frequency is equal to the applied emf, e_1(peak), divided by R_e. By equations 3-4 and 3-5 it can be shown that if $R_L \gg R_d$, R_e approaches the value $\frac{R_L}{2D}$.

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[6] Loc. Cit.

(3-8) $$D = \frac{E_{dc}}{e_1 \text{ (peak)}} = \frac{R_L i_o}{e_1 \text{ (peak)}} .$$

Therefore,

(3-9) $$i_i \text{(peak)} = \frac{e_1 \text{ (peak)} \times R_L i_o}{\frac{R_L}{2} \quad e_1 \text{ (peak)}} = 2i_o .$$

For a given sinusoidal input emf to the rectifier, the amplitude of the fundamental component of current flowing in the diode is very nearly equal to twice the value of the mean d-c current. The harmonic and steady state components of the current take no power from the source and, hence, do not affect R_e.

It has been shown that for a linear diode detector with no condenser across the load,

(3-10) $$E_R = \frac{E_K R_L}{\pi(R_D \quad R_L)} + \frac{M E_K R_L \sin \omega_m t}{\pi(R_D + R_L)}$$

where E_R equals the average voltage across the resistance and E_K equals the peak value of the carrier voltage.[7] The first term of equation 3-10 represents the direct output voltage while the second term, the modulation frequency output voltage.

When only the first term of equation 3-10 is considered, which represents zero per cent modulation, the following relation may be written

(3-11) $$\frac{E_R}{E_K} = \frac{R_L}{\pi(R_D + R_L)} = D$$

which is the expression for rectification efficiency with no condenser across the load. The effective input resistance is given by the relation

(3-12) $$R_e = 2(R_L + R_D)$$

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[7] Reich, Op. Cit., pp. 307-313.

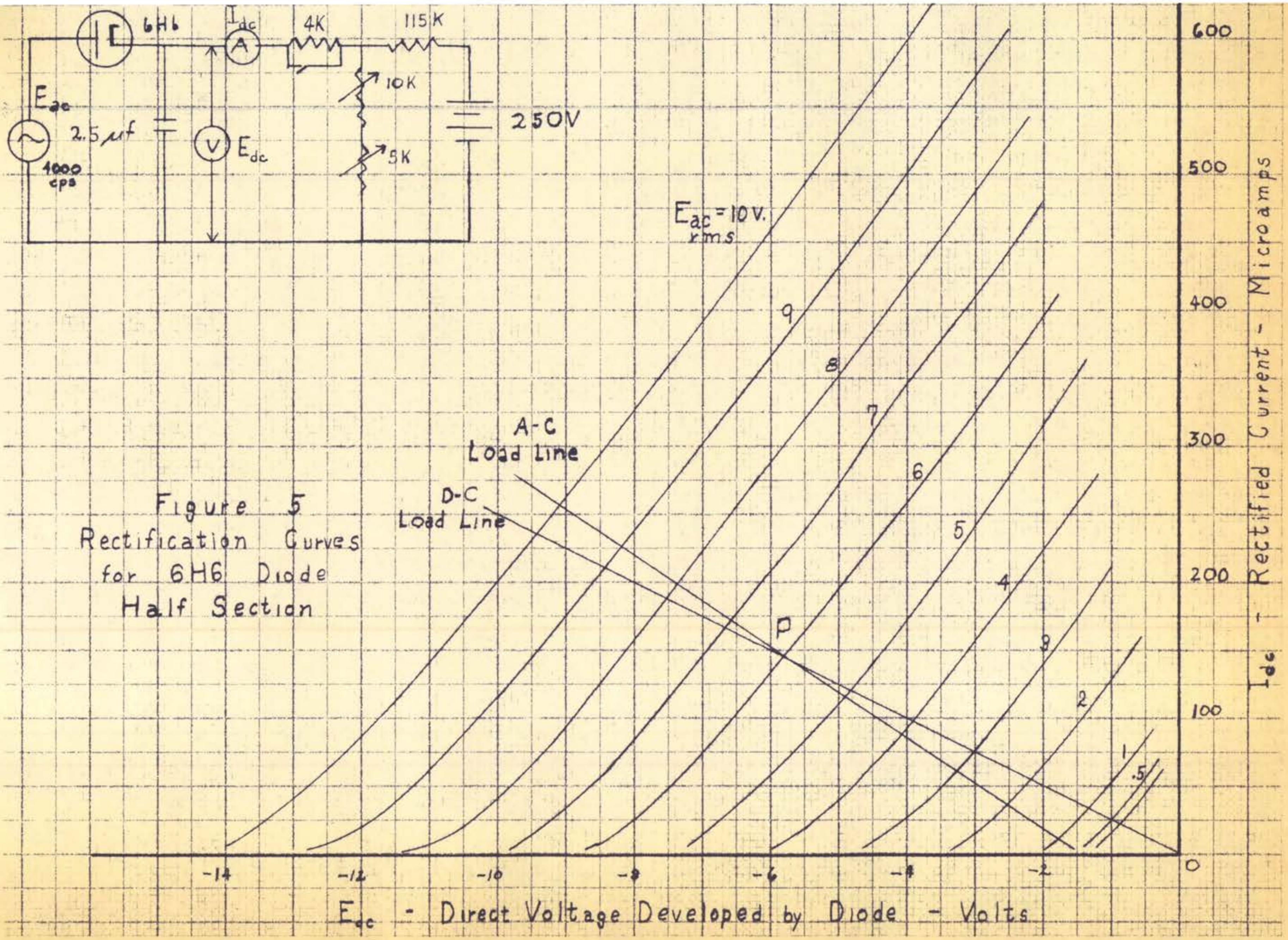

Figure 5
Rectification Curves
for 6H6 Diode
Half Section

CHAPTER IV

CONSTRUCTION OF EQUIPMENT

Realizing the author's interest in research on a-m detectors, Professor Harold T. Fristoe suggested an analysis of a "trick" a-m detector circuit designed by Mr. Robert Ledbetter. Figure 6 shows the circuit used by Mr. Ledbetter.

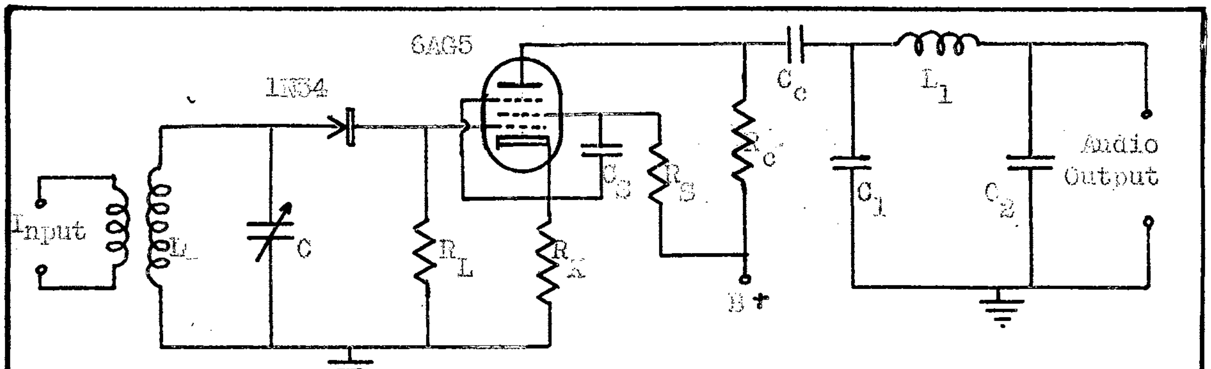

FIGURE 6
Basic Crystal-Driven Amplifying Detector

A. Explanation of Circuit Action

For lack of a better name, this circuit will be called a crystal-driven amplifying detector.

The input signal is a modulated r-f voltage. The tuned tank circuit, LC, is tuned to the input frequency. The input signal appearing across the tuned tank is rectified by the 1N34 germanium diode crystal rectifier. These rectified pulses of modulated r-f current flowing through the crystal load resistor, R_L, provide the necessary voltage to drive the pentode amplifer.

Since modulated r-f pulses appear at the grid of the pentode, the plate current contains a modulating frequency component along with the r-f components. Thus, amplified modulating frequency voltages and r-f voltages appear across the pentode load resistor, R_c. The r-f voltages are then filtered out by the low-pass filter network, $L_1C_1C_2$, leaving only the modulating frequency voltages at the output.

Due to recent developments in microwave equipment, crystal rectifiers of the germanium type have been perfected with high-inverse voltage ratings and current-voltage characteristics that are linear down to a few tenths of a volt. This makes them suited for use as second detectors in low frequency receivers. Since the germanium diode is a non-linear element at low voltages, the voltage applied to the crystal must be of such magnitude as to operate on the linear portion of the current-voltage characteristic. (See Figure 6). Unlike the linear diode detector, there is no condenser in parallel with the crystal load resistor, R_L. This is done purposely so that the r-f pulses produced by rectification are applied to the grid of the pentode amplifier.

The cathode resistor, R_K, is purposely not by-passed to produce degeneration, or negative feedback, for the reduction of amplitude distortion.

One of the factors that limits the response of a diode detector to high percentages of modulation is the difference in the a-c resistance and the d-c resistance of the detector load impedance. This difference is caused by the low reactance of the coupling condenser to modulating frequencies which makes the a-c resistance less than the d-c resistance (see Figure 5) as explained in Chapter III.

In the crystal-driven amplifying detector the pentode serves to isolate the output impedance from the crystal load impedance. Therefore, since the crystal load is resistive, the resistance to the d-c and a-c crystal current components should be the same and negative peak clipping action, which occurs in the diode detector for high values of M, will be eliminated if the pentode is properly biased and the crystal voltage is sufficiently large to provide linear operation.

B. Design of Equipment

Crystal-driven Amplifying Detector - Figure 7 shows the final design of the circuit to be tested. The tank circuit, L_2C_2, is tunable over the broadcast band (550Kc - 1600 Kc). The r-f amplifier stage was included to increase the magnitude of the testing signal. The 6AG5 pentode was designed to operate as a wide band amplifier using a 10K plate load resistor. Operating voltages on the 6AG5 are 200 volts on the plate, 100 volts on the screen and 1.5 volts grid bias with no signal applied. The 1μf screen by-pass condenser was used to give adequate by-passing at low frequencies. The cathode resistor was not by-passed in order to provide degeneration as explained in the previous section. The low pass filter network was designed for a cut-off frequency of 35Kc. The value of R_{g1} is determined by the succeeding tube. A value of 1 megohm was used for R_{g1}. The crystal load resistor R was not assigned a value since it was believed that an optimum value of R could be determined from tests on the 1N34 crystal.

The filter coil, L, was designed and constructed to give proper cut-off frequency and characteristic impedance.

Linear Diode Detector - Since a comparison is to be made of the crystal-driven amplifying detector and the linear diode detector, commonly used in commercial radio, a typical diode detector circuit was designed. (See Figure 8). The single tuned r-f amplifier stage is the same as in Figure 9. One-half of a 6H6 diode serves as the rectifier element. R_1C_1 functions as a resistance-capacitance filter that prevents the r-f ripple voltage, developed across C, from reaching the output terminals. C_c is for the purpose of preventing the d-c component of the rectified output from reaching the output. The diode load resistance to the d-c component consists of $R_1 + R_2$. At modulating frequencies the .1μf coupling condenser, C_c, has negligible reactance and thus the diode load resistance is R_1 in series with the parallel combination of R_2 and R_3.

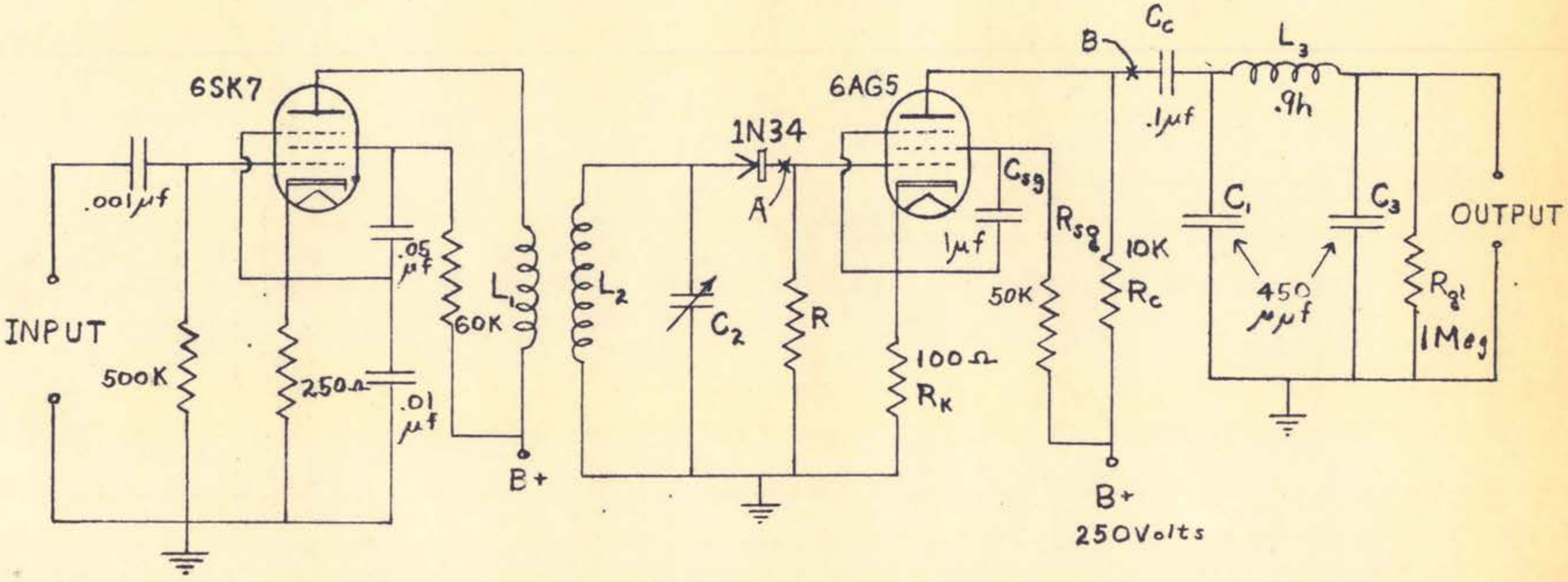

Figure 7.

Crystal-Driven Amplifying Detector

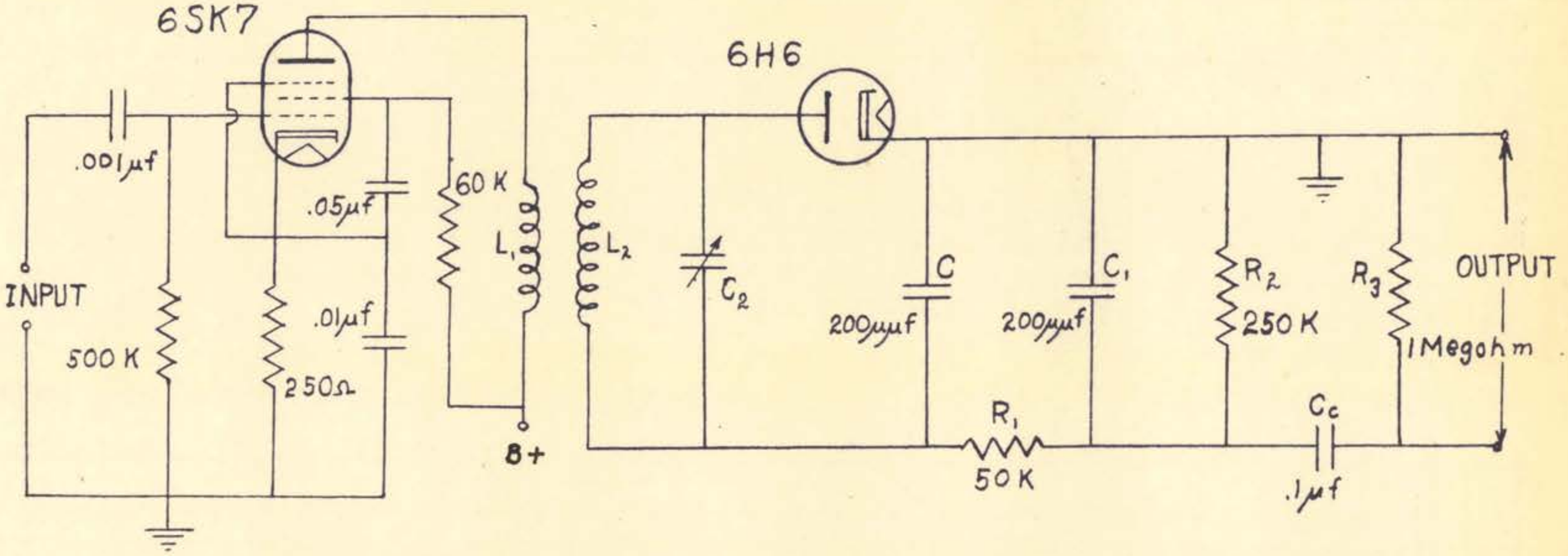

Figure 8

Linear Diode Detector

CHAPTER V

THE INVESTIGATION

It was the purpose of this investigation to compare the operation of the crystal-driven amplifying detector (Figure 7) with the linear diode detector (Figure 8). Similar tests were planned for both circuits, with principle interest directed to frequency response and harmonic distortion for different values of the modulation factor, M, approaching unity. However, it was necessary to perform several preliminary tests to various phases of the two circuits to determine their overall characteristics.

A. Crystal-Driven Amplifying Detector Circuit

The following tests were performed on the overall crystal-driven amplifying circuit and different phases of this circuit.

Rectification Curves for 1N34 Germanium Diode - Data for a set of rectification curves were taken using the circuit on Figure 9. The rectified current, I_{dc}, was measured as a function of the direct voltage, E_{dc}, while the a-c supply voltage was held constant at various values as a parameter. The 4000 ohm resistance in series with the ammeter was inserted to compensate for the ammeter resistance on the low (50μa) range.

Static Crystal Characteristics - Front and back current-voltage characteristics for the 1N34 crystal were measured with the aid of the circuits on Figure 10. To obtain the back characteristic, the crystal voltage, E_x, and the resistor voltage, E_R, were measured for various values of applied voltage, E_t, as shown in Figure 10. The back resistance, R_B, was then calculated from the ratio of E_x to E_R multiplied by R. Crystal current, I_x, was then calculated by the ratio of E_x to R_B. To obtain the front characteristic, the crystal current, I_x, was measured for various values of E_x as shown in Figure 10. An interesting relation is shown by the plot of R_B as E_x (See Figure 11).

Linearity - Measurements were made to determine the linearity of the crystal rectifier (d-c voltage vs a-c input voltage) using several values of crystal load resistance, R, (Figure 5). Load resistors used were 15K, 30K, 100K, and 200K. This test was performed with the crystal in the circuit as in Figure 7. The input was a 600 kilocycle unmodulated r-f voltage. The a-c voltage was measured across the tuned tank, L_2C_2, and the d-c voltage was obtained by placing an ammeter in series with R by-passed with a .25μf condenser. Average d-c was the ammeter reading times R. The result of this test is shown in Figure 12.

Frequency Response and Wave Analysis - A fixed carrier frequency of 600 kilocycles was applied to the input of the circuit in Figure 8. Modulation of the carrier was provided by an audio signal generator. The audio output voltage, E_o, was measured as a function of modulating frequency (50cps - 10Kc) with the modulation percentage held constant at various values (30%, 50%, 70%, 80%) as a parameter. Maximum degree of modulation attainable with the r-f signal generator used was 80 per cent. At each measurement above, a wave analyzer was connected to the audio output and the values of the fundamental and harmonic voltages were measured.

Frequency Response of Audio Stage - The circuit of Figure 7 was disconnected at point A and a signal generator connected at that point. The grid voltage, E_i, on the 6AC5 was held constant at one-half volt. E_o, the audio output, was measured for various frequencies of the applied voltage (50cps - 40 Kc). The response of the 6AG5 pentode was checked in a similar manner. The circuit was disconnected at point B and the voltage across the plate load resistor, R_c, was measured for various frequencies of applied voltage (50cps - 5Mc). Also, the response of the load impedance after point B was checked for a range of frequencies from 50cps to 40Kc.

Wave Analysis of Amplifier Stage - A square wave signal was applied at point A of Figure 7 and the output observed with a cathode-ray oscilloscope.

B. Tests of Linear Diode Detector

The testing procedure of the diode detector was similar to that for the crystal-driven amplifying detector.

Rectification Curves - A set of rectification curves was obtained with the aid of the circuit on Figure 8. I_{dc} was measured as a function of E_{dc} as the supply voltage, E_{ac}, was held constant at various values as a parameter.

Linearity - The direct bias voltage developed across R_2 (Figure 8) by the diode detector was measured as a function of the a-c applied voltage measured across the tuned tank circuit.

Frequency Response and Wave Analysis - This test procedure was identical to that given in Section A of this chapter.

In the above tests, voltages were measured with a Hewlett-Packard vacuum tube voltmeter, Model 410A, and current was measured with a Triplett ammeter, Model 1200-F. The source of modulated r-f voltage was a General Radio signal generator, Type 1001-A, which has a frequency range of 5 kilocycles to 50 megacycles. Modulating voltages were supplied with an audio signal generator of local manufacture. Wave forms were observed with a Dumont cathode-ray oscilloscope, Model 208-B.

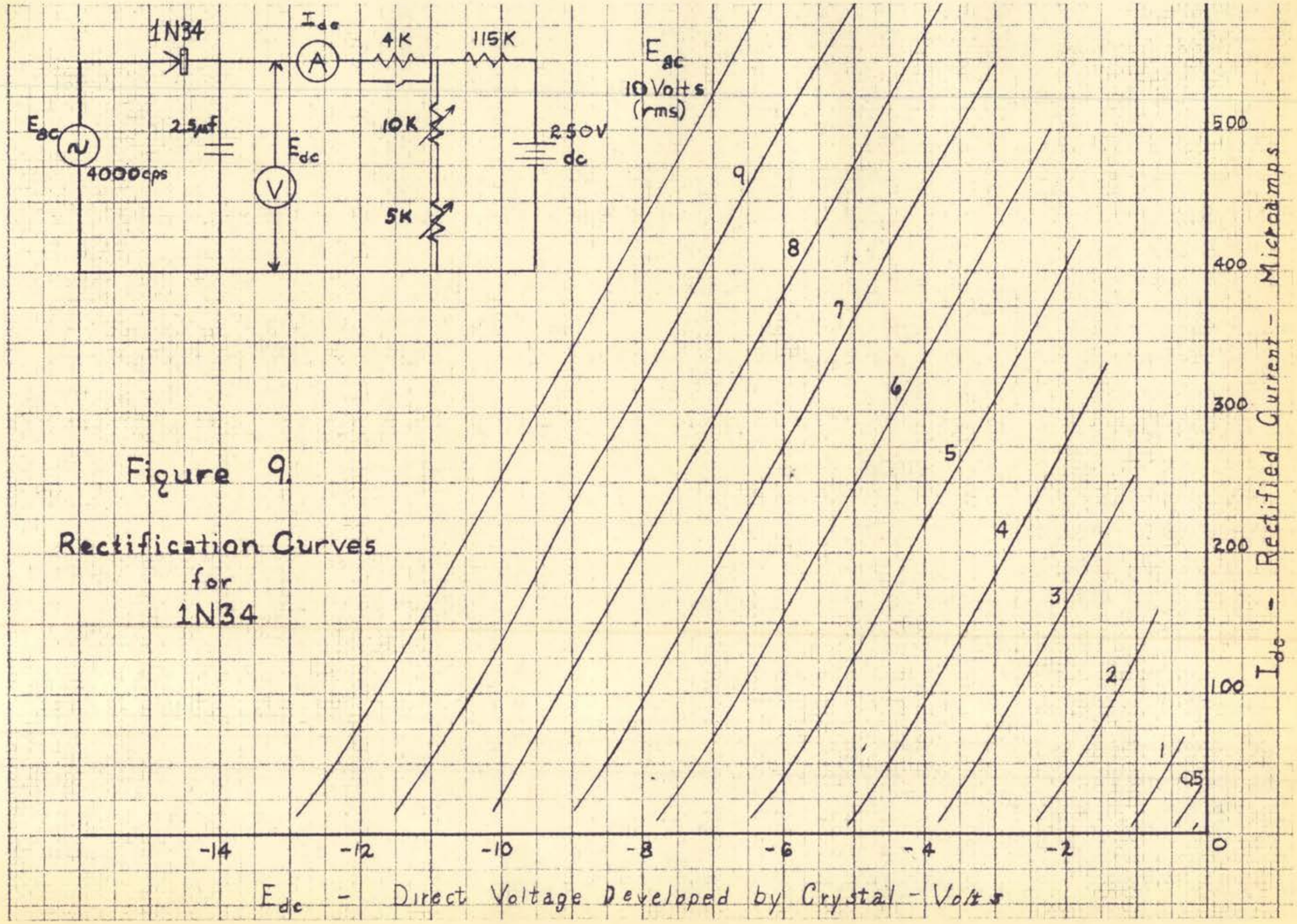

Figure 9.

Rectification Curves for 1N34

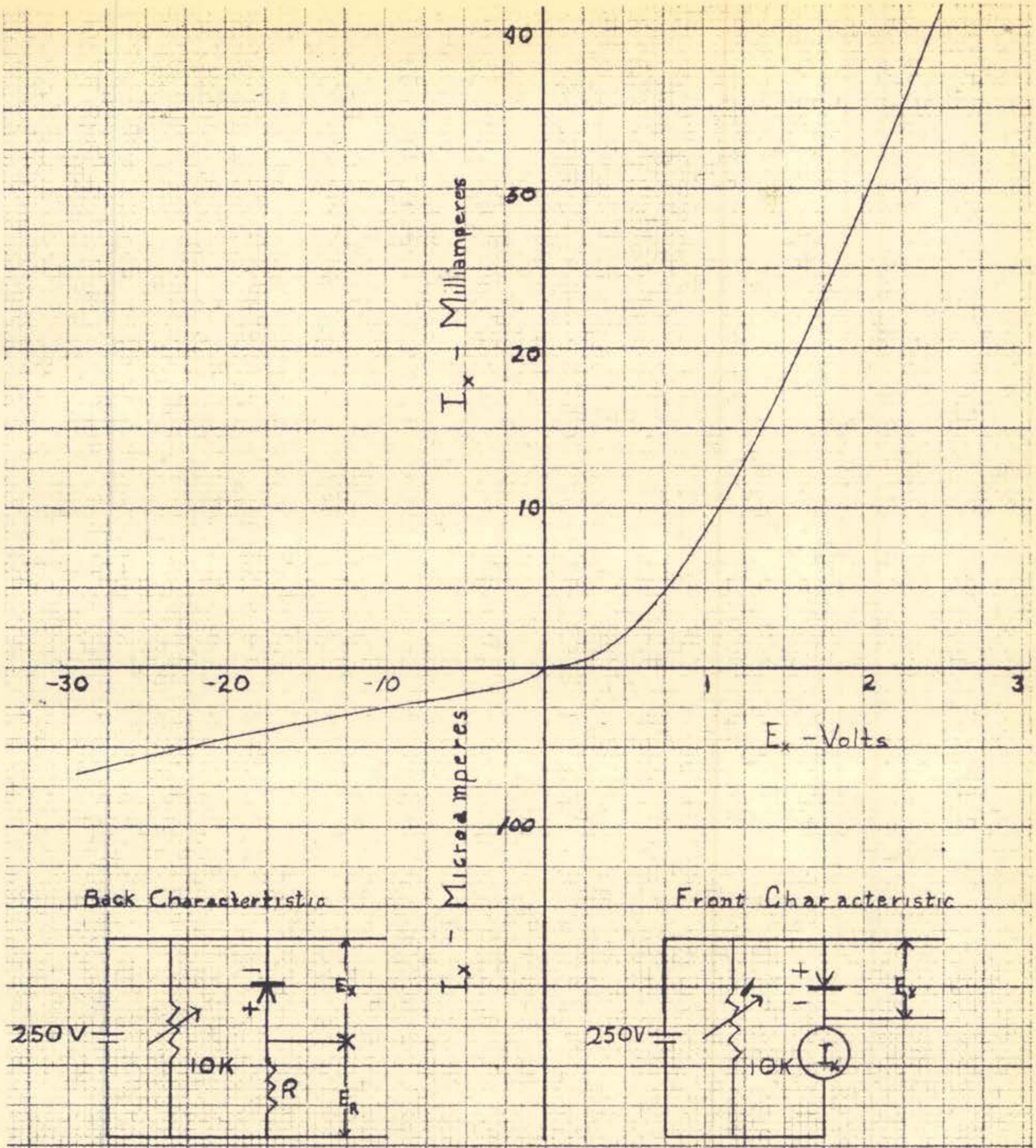

Figure 10.

Current-Voltage Characteristics for a 1N34 Crystal

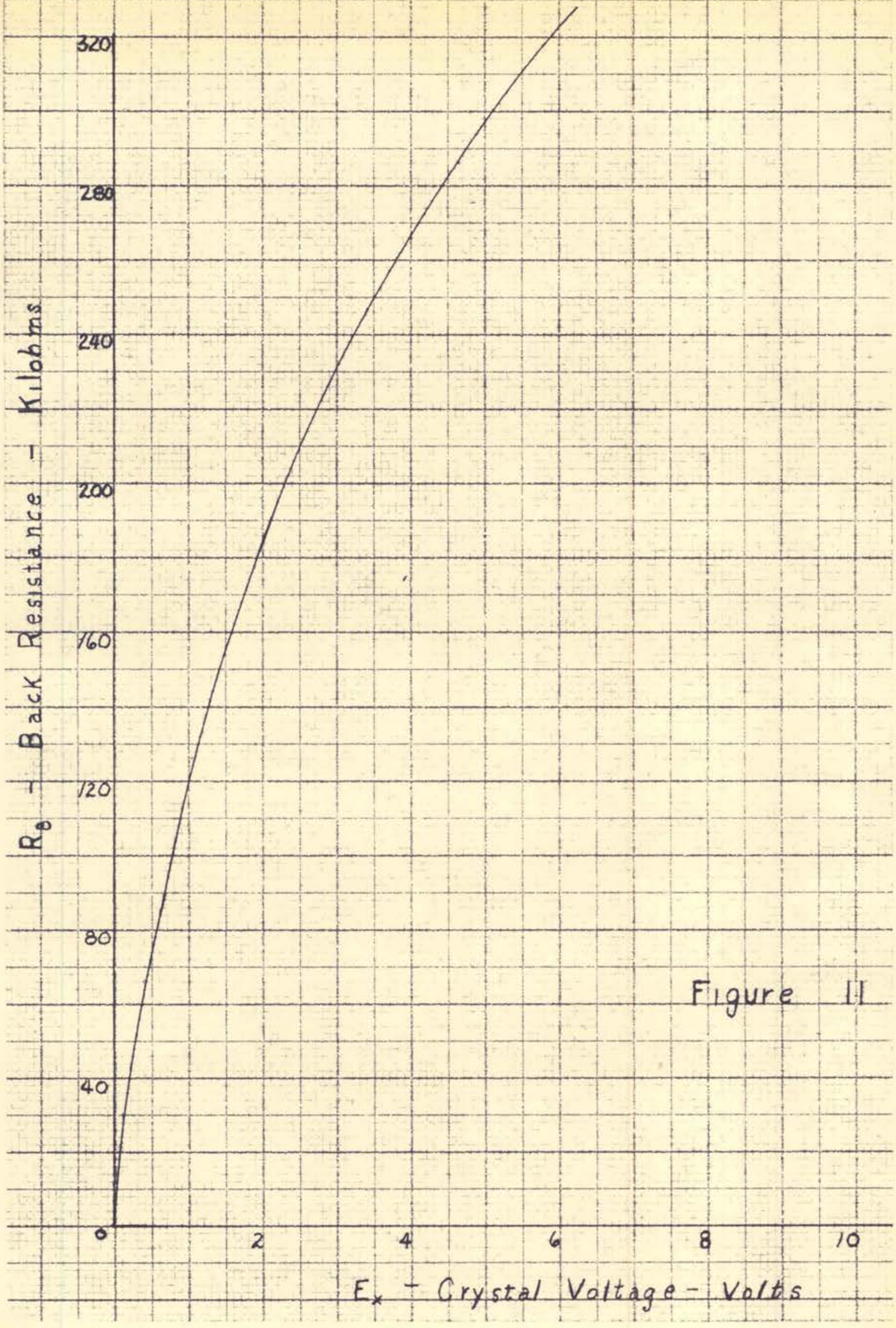
320
280
240
200
160
120
80
40
0
2
4
6
8
10
R_B - Back Resistance - Kilohms
E_x - Crystal Voltage - Volts

Figure II

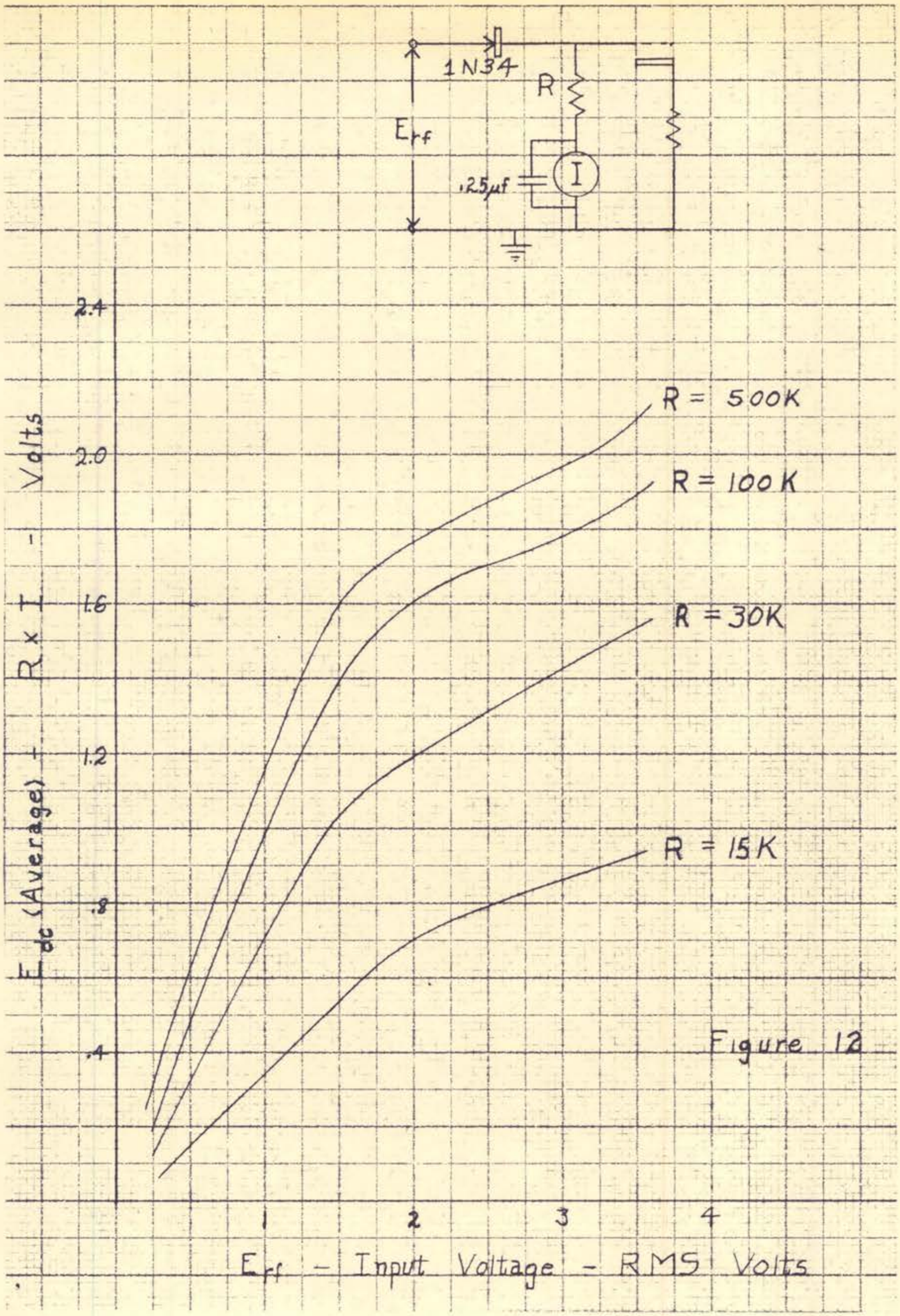
1N34
R
E_rf
.25μf
I
2.4
2.0
1.6
1.2
.8
.4
E_dc (Average) - R x I - Volts
R = 500K
R = 100K
R = 30K
R = 15K
1
2
3
4
E_rf - Input Voltage - RMS Volts

Figure 12

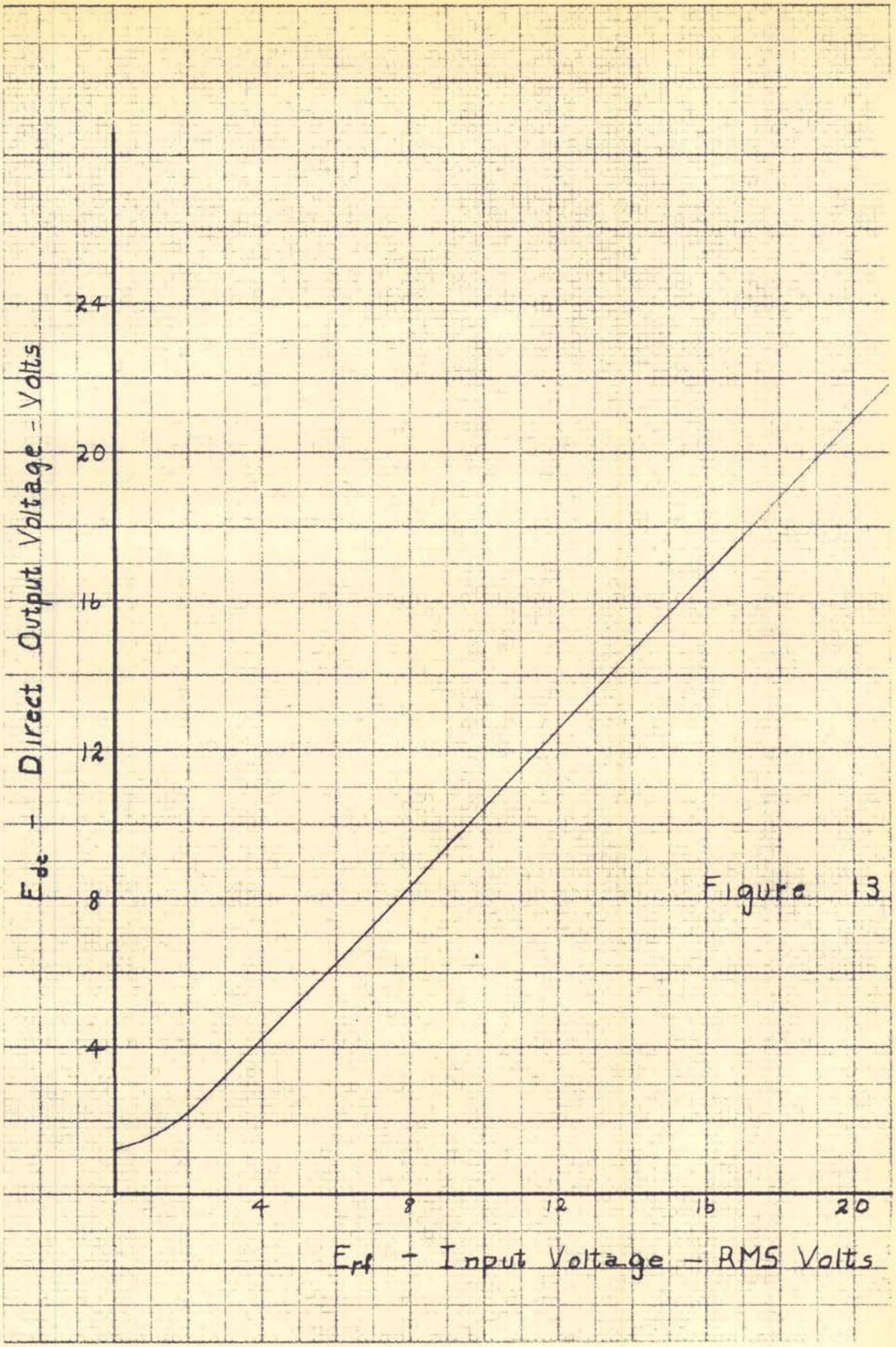
E_{dc} - Direct Output Voltage - Volts
24
20
16
12
8
4
4
8
12
16
20
E_{rf} - Input Voltage - RMS Volts

Figure 13

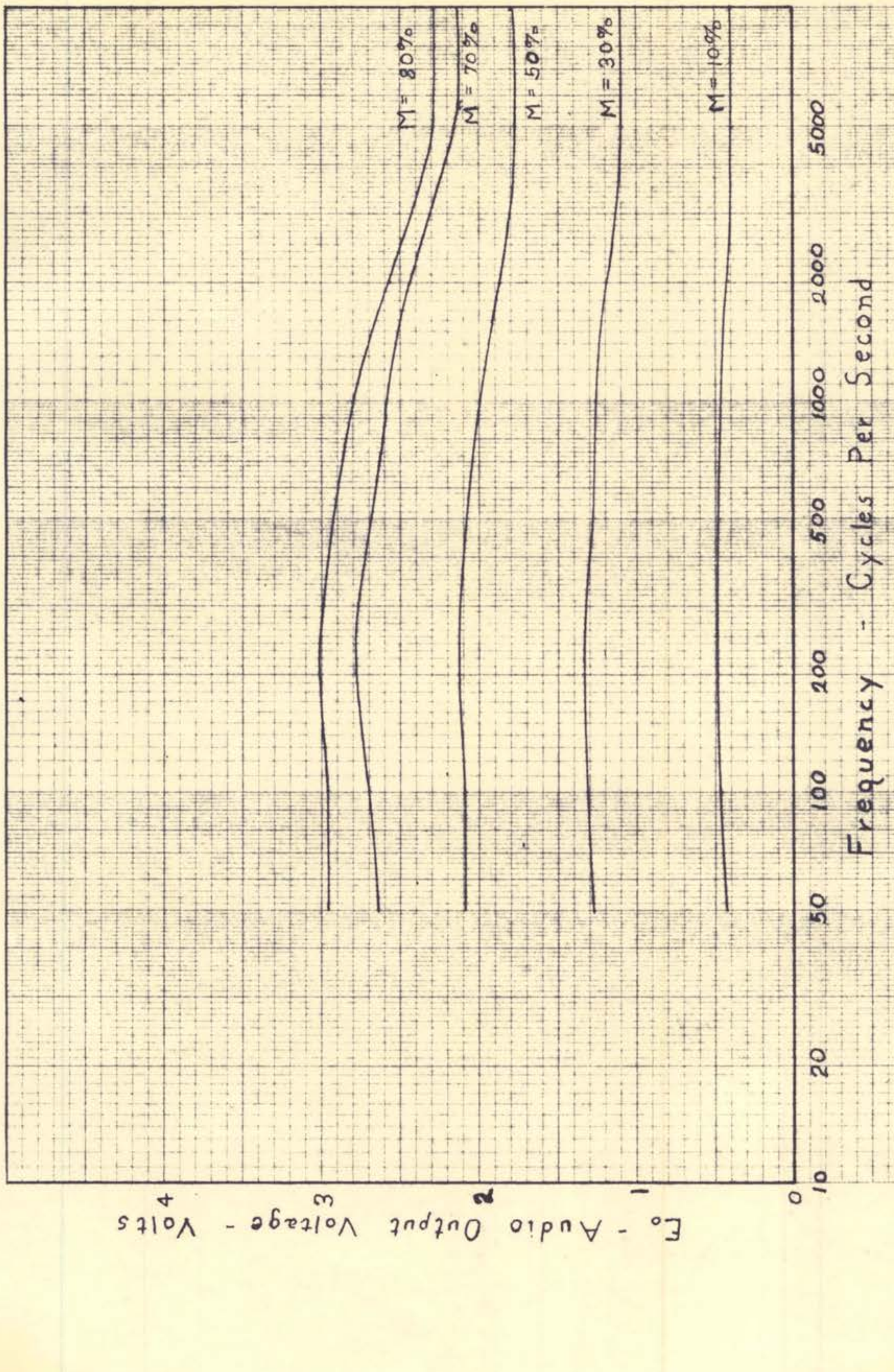
M = 80%
M = 70%
M = 50%
M = 30%
M = 10%
10
20
50
100
200
500
1000
2000
5000
Frequency - Cycles Per Second
0
1
2
3
4
E₀ - Audio Output Voltage - Volts

Figure 14

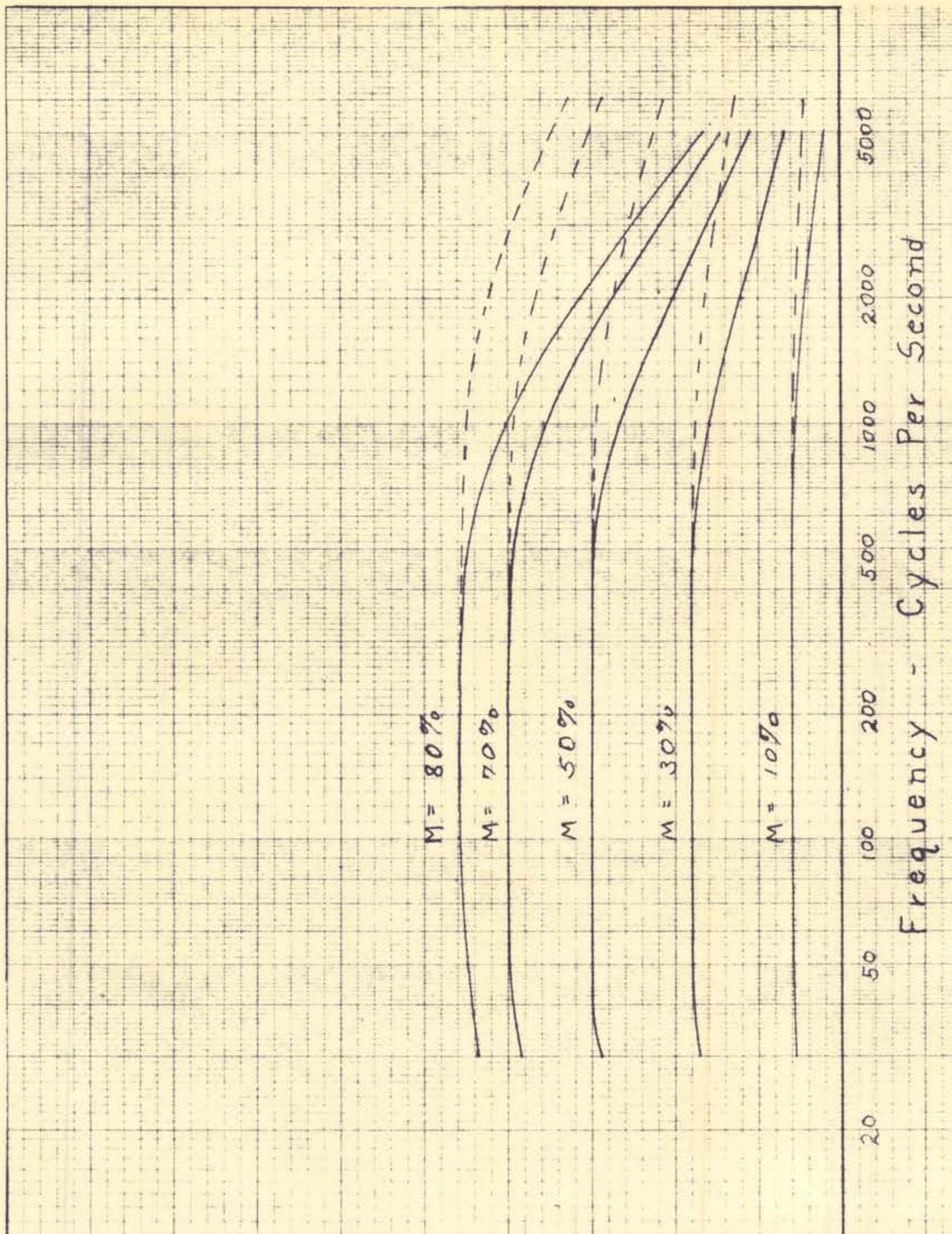
M = 80%
M = 70%
M = 50%
M = 30%
M = 10%
10
20
50
100
200
500
1000
2000
5000
Frequency - Cycles Per Second
0
1
2
3
Eo - Audio Output Voltage - Volts

Figure 15

CHAPTER VI

INTERPRETATION OF DATA

Rectification curves for a 1N34 germanium diode crystal are shown in Figure 9. The rectifying circuit in the crystal-driven amplifying detector used no condenser in parallel with the load resistance; therefore, rectification curves for the 1N34 crystal cannot be used to determine the rectification efficiency or the load voltage and current. However, since a set of rectification curves shows the characteristic of the rectifying element alone, a comparison of the characteristics of the 1N34 crystal and the 6H6 diode may be obtained by comparing their rectification curves. A comparison of Figure 5 with Figure 9 shows the curves of the 1N34 to be more steeply inclined, less curved, and more evenly spaced at low values of applied voltage than the curves of the 6H6 diode.

An important step in designing the crystal-driven amplifying detector is the determination of the value of the crystal load resistor, R_L. Unlike a diode rectifier, a crystal rectifier will conduct when a negative voltage is applied to it. This is the same as saying that the back resistance of a diode is much greater than the back resistance of a crystal.

Since the crystal in this circuit conducts during the entire positive half cycle of input signal, the voltage across R_L depends on the ratio of R_L to R_F, the crystal forward resistance. During the negative half cycle of the input signal, the voltage across R_L depends on the ratio of R_L to R_B, the crystal back resistance. Ideally, R_B would be very much larger than R_L and R_L would be very much larger than R_F. Figure 11 shows a plot of back resistance vs crystal back voltage. At values of crystal voltage below two volts, R_B is of the order of 100 K. R_L must then be considerably lower than this value and at the same time, must be much larger than R_F. R_F increases exponentially as crystal forward voltage decreases and is of the order of 400 ohms at three-tenths of a volt forward voltage.

In the analysis of a linear detector using a crystal as the rectifying element with no condenser across the load resistance, as in the case with the crystal-driven amplifying detector, the expression for the direct voltage across the load resistance would be similar to equation 3-10 for low values of load resistance. The reason for this is that for low values of R_L, the pulses of plate current approximate a half sine wave of amplitude as in equation 3-10, while for large values of R_L, which approach the back resistance of the crystal, plate current flows during the negative half cycles of input voltage.

Equation 3-11 shows then, that the rectification efficiency decreases with the omission of the condenser across the load resistor. In the circuit under test, the rectification efficiency was calculated to be between .2 and .25, the difference being caused by the change in the dynamic resistance of the crystal. The effective input resistance was found to be approximately 40,000 ohms, which lowered the Q of the tuned tank to about one-third of the value obtained when a condenser was used across the load.

In the circuit of Figure 7 the voltage applied to the grid of the pentode amplifier must not be over one volt to prevent overdriving the grid since the bias is only 1.5 volts. Considering this fact and then determining the values of R_F and R_B from Figure 11, an optimum value of R_L can be found. The value of R_L used was 15 K. A lower value of R_L would satisfy the relation, $R_B \gg R_L \gg R_F$, but would seriously load the tuned tank circuit. Also, with a 15K load resistance, the linearity of the rectifier is better than for larger values of load resistance. Figure 12 shows the rectifier linearity for several values of R_L. The curved portion of the curves was caused by the crystal voltage operating over the non-linear portion of the current-voltage characteristic.

Figure 13 gives an indication of the linearity of the linear diode detector. For values of input voltage above one volt, the direct output voltage is directly proportional to the applied voltage.

The frequency response of the crystal-driven detector was very good. (See Figure 14). At a modulation frequency of five kilocycles and 80 per cent modulation, the audio output dropped off to 76 per cent of its maximum value. The response was flat well over the range of modulating frequencies ordinarily used in broadcasting which is usually a maximum of four kilocycles, but may be as high as 10 kilocycles depending on the fidelity desired. The bandwidth of the tuned tank circuit at the input to the detector was very wide due to a low Q which was caused by the low input impedance of the rectifier circuit. The bandwidth was approximately 20 kilocycles. The ordinates on Figure 14 are measured values of output voltage when the input voltage was .8 volts (rms) measured across the tuned circuit, L_2C_2, with no modulation applied.

Figure 15 shows a similar set of response curves for the linear diode detector. It was noted that the relative output dropped off considerably at about two kilocycles. It was found that the bandwidth was only about seven kilocycles and could be increased to about 12 kilocycles by lowering the Q of the tank circuit sufficiently. The dotted lines show the response with increased bandwidth. The ordinates on Figure 15 are measured values of output voltage when the input voltage was five volts (rms) measured across the tuned circuit, L_2C_2, with no modulation applied.

The result of the wave analysis shows that there is very little difference in the amount of harmonic distortion produced by the two types of detectors. Although the amount of harmonic distortion produced by the crystal-driven amplifying detector was generally slightly higher, the total distortion factor in both cases never exceeded .05 (five per cent), a value which is not objectionable. Distortion factor, δ, was calculated from the relation,

$$\delta = \frac{\sqrt{H_2^2 + H_3^3 + H_4^4 + \ldots\ldots}}{H_1}$$

where H represents the amplitude of the harmonic component and the subscript represents the order of the harmonic.

The purpose in performing the wave analysis was to show whether or not excessive distortion would be produced as the percentage modulation was increased toward unity. This phase of the testing procedure was handicapped by the fact that the r-f signal generator used to produce modulation would only modulate up to 80 per cent. This is below the point where cut-off, or negative peak clipping distortion, starts in the linear diode detector under test.

One of the things responsible for the high amount of distortion produced in the crystal-driven detector is the fact that the cut-off frequency of the low-pass filter network is higher than the cut-off frequency of the filter network in the diode detector output circuit. A higher cut-off frequency will pass more of the higher-order harmonics which cause objectionable tones in the audio output. Also intermodulation frequencies appear more readily in the crystal-driven detector because of the use of two non-linear devices (the crystal and the pentode) in the circuit.

The response of the pentode amplifier, when isolated, proved to be flat over a frequency range of 50 cycles per second to two megacycles. The response of the amplifier and filter network alone was flat from 50 cycles per second to 10 kilocycles. At about 20 kilocycles a sharp resonant peak occurred in the output voltage. This was caused by the input frequency passing through the resonant frequency of the filter network. A resonant peak of this sort results in greater amplification of frequencies from about 10 kilocycles to 30 kilocycles. However, since the resonant frequency is much greater than the maximum modulating frequency usually encountered, components of frequencies close to the resonant frequency will be the result of harmonics or intermodulation frequencies and will have very small magnitudes.

It was shown by the application of a square wave signal to the grid of the 6AG5 that considerable phase distortion was present at low frequencies. The output voltage led the input voltage which was expected. At high frequencies, however, there was very little phase distortion.

On all tests requiring a modulated r-f signal as the detector input, the carrier level with maximum percentage modulation was held constant throughout the test at a magnitude just below the value that would produce a grid voltage sufficient to overdrive the pentode amplifier. Any appreciable increase in the carrier level caused a marked increase in the distortion of the output waveform. In actual practice this would mean that a signal from one station may produce a grid voltage of proper magnitude while a signal from a stronger station would overdrive the pentode amplifier and serious distortion would result. Therefore, it is essential that the crystal-driven amplifying detector supply a source of avc voltage to maintain the detector input constant. A possible means of doing this is to apply the input voltage across the tuned tank through a small condenser to the grid of a triode amplifier whose cathode is at a negative potential with respect to ground. An amplified avc voltage may then be obtained from the plate circuit of the amplifier across a resistor tied directly to ground.

An avc voltage may be obtained with the linear diode detector without the need for a separate tube. At a point between R_1 and R_2 on Figure 8, a negative avc voltage that is proportional to the amplitude of the input signal may be fed back to previous r-f or i-f amplifiers through a large series resistor and by-pass condenser.

In an actual receiver such as the very popular superheterodyne receiver, the detector input would be the output of an intermediate-frequency amplifier with a frequency of either 455 kilocycles or 175 kilocycles. A frequency of 600 kilocycles was used as the input frequency for the detectors under test to facilitate the use of a variable 35 - 365$\mu\mu$f tuning condenser with which greater ease in manipulation of the tests were permitted.

CHAPTER VII

CONCLUSIONS

From the results of the preceding tests it was concluded that the crystal-driven amplifying detector was inferior to the linear diode detector. The bases for this statement is born out by the following observations.

The use of a pure resistive load for the 1N34 crystal rectifier lowers the rectification efficiency. The use of low values of load resistance that are necessary for proper rectification also tends to lower the rectification efficiency and at the same time lowers the effective input resistance of the detector. The resulting low Q of the tuned circuit destroys some of the selectivity of the last i-f amplifier stage.

The grid voltage applied to the 6AG5 pentode amplifier must be held constant to prevent overdriving the grid. With 1.5 volts grid bias, a constant grid voltage of five-tenths to one volt would properly drive the pentode amplifier. A separate tube is required to provide the necessary avc voltage to keep the detector input constant.

There is a possibility that the crystal-driven amplifying detector will produce less distortion than the linear diode detector at high percentages of modulation, however, it was not possible to show this since the maximum degree of modulation attainable with the signal generator used was 80 per cent.

It is doubtful that the crystal-driven amplifying detector would give less distortion with the higher degrees of modulation because of the various places where distortion could be introduced. The crystal, being a non-linear element along with the 6AG5, whose plate current-grid voltage characteristics are non-linear, will produce voltage components of harmonic frequencies in the output. The linear diode detector, having a non-linear current-voltage characteristic only for low voltages, produces very little harmonic distortion as long as the applied voltage is sufficiently large.

The sensitivity of the crystal-driven amplifying detector was better than for the linear diode detector. This was due to the amplification supplied by the pentode. However, the amplification was much lower than usually expected with a pentode tube. This was partly due to the degeneration produced by the cathode resistor being not by-passed, and partly due to the low value of plate resistance used.

The properties of a germanium diode crystal rectifier such as the 1N34 make it appear more practical for use as a second detector in an a-m receiver. However, when used as in the crystal-driven amplifying detector some of its advantages are lost. For example, the bias voltage produced with a condenser across the load makes the back resistance much higher than when no condenser is used as shown in Figure 11.

In preparing this paper it was realized why the linear diode detector is so popular and so widely used. With proper design of the load circuit, the audio output can be made to follow almost exactly the variations of the carrier envelope. By using a large load resistor, the detection efficiency can be made to approach 90 per cent and the maximum percentage modulation without cut-off distortion will approach 90 per cent.

An economic disadvantage of the crystal-driven amplifying detector is the need for so many circuit components. When an avc voltage is developed, two vacuum tubes and a crystal rectifier are necessary, while a linear diode detector requires only one vacuum tube to provide similar operation.

BIBLIOGRAPHY

Arguimbau, L. B. *Vacuum Tube Circuits.* New York: John Wiley and Sons, Inc., 1948.

Ballantine, Stuart. "Detection of High Signal Voltages." *Proceedings of the Institute of Radio Engineers*, XVII (1929), 1153.

Bennon, S. "Notes on Large Signal Diode Detection." *Proceedings of the Institute of Radio Engineers*, XXV (1937), 1565.

Cocking, W. T. "Detector Input Circuit." *Wireless Engineering and Experimental Wireless*, XII (1935), 595-599.

Cruft Memorial Laboratory Staff, Harvard University. *Electronic Circuits and Tubes.* New York: McGraw-Hill Book Company, Inc., 1947.

Eastman, Austin V. *Fundamentals of Vacuum Tubes.* New York: The McGraw-Hill Book Company, Inc., 1949.

Fubini, E. G. and Johnson, D. C. "Signal to Noise Ratio in Non-Linear Transmission Circuits." *Proceedings of the Institute of Radio Engineers*, XXXVI (1948), 1967-1977.

Kilgour, F. E. and Nelson, J. R. "Diode Detection Analysis." *Proceedings of the Institute of Radio Engineers*, XI (1933), 930-943.

Massachusetts Institute of Technology Staff. *Applied Electronics.* New York: John Wiley and Sons, Inc., 1949.

Middleton, D. "Rectification of Sinusoidically Modulated Carrier in Presence of Noise." *Proceedings of the Institute of Radio Engineers.* XXXVI (1948), 1967-1977.

Reich, H. J. *Theory and Applications of Electron Tubes.* New York: The McGraw-Hill Book Company, Inc., 1944.

Roberts, F. and Williams, F. C. "Straight Line Detection With Diodes." *Journal of Institute of Electrical Engineers*, LXXV (1934), 379-388.

Terman, F. E. *Radio Engineering.* New York: The McGraw-Hill Book Company, Inc., 1947.

Terman, F. E. and Nelson, F. R. "Discussion of 'Some Notes on Grid-Circuit and Diode Rectification'." *Proceedings of the Institute of Radio Engineers*, XX (1932), 1971-1974.

Torrey, H. C. and Whitmer, Charles A. *Crystal Rectifiers.* New York: The McGraw-Hill Book Company, Inc., 1948.

Wheeler, Harold A. "Design Formulas for Diode Detectors." *Proceedings of the Institute of Radio Engineers*, XXVI (1938), 745.

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