Discriminator comparison
by Robert H Shennum

A THESIS Submitted to the Graduate Committee in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University

Abstract:

Discriminators have been in wide use in the fields of FM radio and automatic frequency control foy several years. Several articles have been published concerning particular applications of discriminators in which detailed analysis has been included, The purpose of this thesis was to present a simple method of obtaining the approximate, operating characteristics of the common discriminator circuits, and to compare the principal types with reference to their chief applications.

Three discriminators are described in detail in this thesis. These are the basic circuits used in most commercial work. The tests on each of the circuits include, determination of linearity, measure of sensitivity, ease of adjustment and dependence upon tube constants. The comparison of the three discriminators on each of these bases is included in the summary, The varied purposes for which discriminators are used make a general comparison of little value. Each discriminator has particular characteristics which make it more suited to one use than to another. The circuits discussed are compared on the basis of each of the chief commercial applications and the relative advantages and disadvantages of the, circuits for each application are considered.

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Bozeman, Montana
June, 1948

ACKNOWLEDGMENT

The work of this thesis was undertaken at the suggestion of, and under the guidance of, Dr. E. W. Schilling, Dean of Engineering, and Professor R. C. Seibel of the Electrical Engineering Department of Montana State College. The author expresses his appreciation to Dr. Schilling and to the other members of the Electrical Engineering staff for their kind help and suggestions and particularly to Professor Seibel, under whose direct supervision the work was completed.

Robert H Shennum

g. Graduate Committee

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ABSTRACT

Discriminators have been in wide use in the fields of FM radio and automatic frequency control for several years. Several articles have been published concerning particular applications of discriminators in which detailed analysis has been included. The purpose of this thesis was to present a simple method of obtaining the approximate operating characteristics of the common discriminator circuits, and to compare the principal types with reference to their chief applications.

Three discriminators are described in detail in this thesis. These are the basic circuits used in most commercial work. The tests on each of the circuits include determination of linearity, measure of sensitivity, ease of adjustment and dependence upon tube constants. The comparison of the three discriminators on each of these bases is included in the summary. The varied purposes for which discriminators are used make a general comparison of little value. Each discriminator has particular characteristics which make it more suited to one use than to another. The circuits discussed are compared on the basis of each of the chief commercial applications and the relative advantages and disadvantages of the circuits for each application are considered.

INTRODUCTION

In literature dealing with discriminators, and frequency modulated equipment in general, several abbreviations are used which, while not accepted in our general English vocabulary, are used to save writing time and space. The letters FM are universally used, even by the general public, to mean frequency modulation. Similarly throughout this thesis the abbreviations AM for amplitude modulation, and PM for phase modulation will be used. In dealing with coupled circuits the "Q" factor, the so-called figure of merit, of a coil is found, and in the remainder of this text will be used without explanation. Other accepted abbreviations, such as kc. for kilocycle, as are used in the field of radio engineering, are assumed to be well known to the reader.

The aim of the research leading to this thesis was to obtain information as to the relative merits of commercial discriminator circuits, and to determine basic information about each of the important types. There has been considerable research done on special applications of circuits studied in this thesis but to the knowledge of the writer, no article has been written in which a detailed comparison of discriminators has been made. In the "Literature Cited and Consulted" section of this thesis the most important works in the field of detection of FM and automatic frequency control are found. These are the two most widely used applications of the discriminator.

Discriminators were first used by Travis and by Foster and Seeley for the purpose of obtaining a means of controlling frequency of oscillators automatically, so that a receiver tuned to a particular station would remain on the frequency of the desired transmitter, even though there might be changes in circuit constants of either the transmitter or receiver. Their work was chiefly of an experimental nature. Later the circuits used were analyzed by Roder, Jaffe and others so that the discriminators could be improved in linearity and sensitivity. This thesis shows both new methods of analysis and refinements on the methods of earlier writers, which justify the experimental results obtained and allow analytical comparison of the different types studied.

The data used to plot curves, and for other comparisons, was obtained as a result of laboratory work on the particular circuits shown. In all cases this equipment was built by the writer, as commercial equipment was not available here, and in many cases was not to be found on any companies' sales list.

In general, the laboratory work preceeded the analysis. This seemed to be the most logical approach to the problem since in this way the actual experimental comparison of operating characteristics was obtained, and was then followed by analytical proof of conclusions made on this experimental basis.

DISCRIMINATOR FUNDAMENTALS

There are three basic types of discriminator circuits, each of which has been modified many times for particular purposes. The first one considered in this thesis will be the capacitive coupled type generally known as the Foster-Seeley circuit. The second type referred to as the Seeley-Kimball-Barco discriminator depends on resistance-capacity networks and the last is known as the Travis circuit, although it is sometimes referred to as the Crosby discriminator. It depends upon inductive coupling for transfer of power.

The frequency at which a discriminator is designed to operate is dependent upon the application to which it is to be applied. In all the laboratory work done in connection with this report a center frequency of 500 kilocycles was used. This would be a common frequency for automatic frequency control, and was approximately the intermediate frequency used in early FM receivers. In later receivers a center frequency in the order of 5 megacycles was used. With the recent change in F. C. C. allocation of frequencies in which the FM band was changed to 88 to 108 megacycles, new center frequencies are used. The intermediate frequency must be chosen in a FM receiver to obtain maximum image rejection so a center frequency of 10.7 megacycles is recommended by the RMA.

The analytical work done in circuit analysis is not dependent upon the particular frequency chosen however, so there is no loss of generality in the results obtained. For the laboratory equipment available it seemed advisable to use a low resting frequency. In some cases[1] discriminators have been constructed for use in the audio-frequency band so that there is no general or accepted reference for all uses.

A short discussion of the characteristics of diode vacuum tubes is included in this work. The effective resistance of these tubes is of such prime importance in the analysis of all discriminator circuits that the writer considered this additional work necessary to make the explanations complete. For commercial applications all circuits must be so constructed that changing tubes will not seriously affect operation, or so that the circuit may be readily adjusted to compensate for any differences that may be found in the tubes. In addition to actual changes in tubes it is found that the aging of tubes has some effect on their characteristics, particularly in the case of diodes. The emission of a tube tends to be less as the age increases, and this effectively increases the equivalent resistance that the tube presents. In circuits such as the Seeley-Kimball-Barco discriminator

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1. Western Electric set AN/FGC-1 uses a center frequency of 2125 cycles for automatic frequency control.

where the operation is dependent upon time constants, the change in tube resistance may radically alter the characteristics of the circuit.

THE FOSTER-SEELEY DISCRIMINATOR

In a study of characteristics of any discriminator, the linearity with which the circuit reproduces intelligence from the frequency modulated wave is of first importance. For an analysis of this characteristic it need only be known what output voltage is produced by a series of sinusoidal waves, as any complex wave may be analyzed into a series of sinusoidal components. In the case of a FM wave the analysis takes the form of an infinite series of harmonics together with a fundamental frequency. The harmonics differ from the carrier or fundamental frequency by integer multiples of the modulating frequency.

In the laboratory test of the linearity of each discriminator the procedure was the same. A series of measurements of output voltage as a function of sinusoidal input frequency were made. A graph of these points should give a straight line for a perfect discriminator, since it is desired that the discriminator output shall be a direct function of the amount by which the input frequency differs from the center frequency.

The series of curves of Fig. 1 show the actual operating characteristics of the circuit. The discussion which follows explains the method used to obtain the curve labeled "computed output". While the agreement of the experimental and calculated results is not perfect, it is to be noted that the deviation is in a range which is nonlinear so that this portion is of no value as a detector. The two curves agree within less than 1% over the useful range of the circuit.

For practical purposes the useful frequency range, in which distortion is negligible, is of considerable interest. Experimental results indicate that for the particular circuit tested this width is approximately 8 kc. When this is compared with the experimentally determined separation of peak output voltage points, it is noted that the linear part of the curve is slightly less than half the total width. This agrees favorably with the work of others.[1]

Since the value of frequency range in kilocycles is of little significance without a fixed and specified center or resting frequency, the usual method of comparison is by stating the useable range in terms of the Q's of the coils and the center frequency "F". In the particular discriminator tested the Q of the primary and secondary coils was the same. The separation of peak voltages measured in Kilocycles was

$$W = \frac{0.8 \times F}{\sqrt{Q_p \, Q_s}} \qquad \text{.......................} \quad 1.$$

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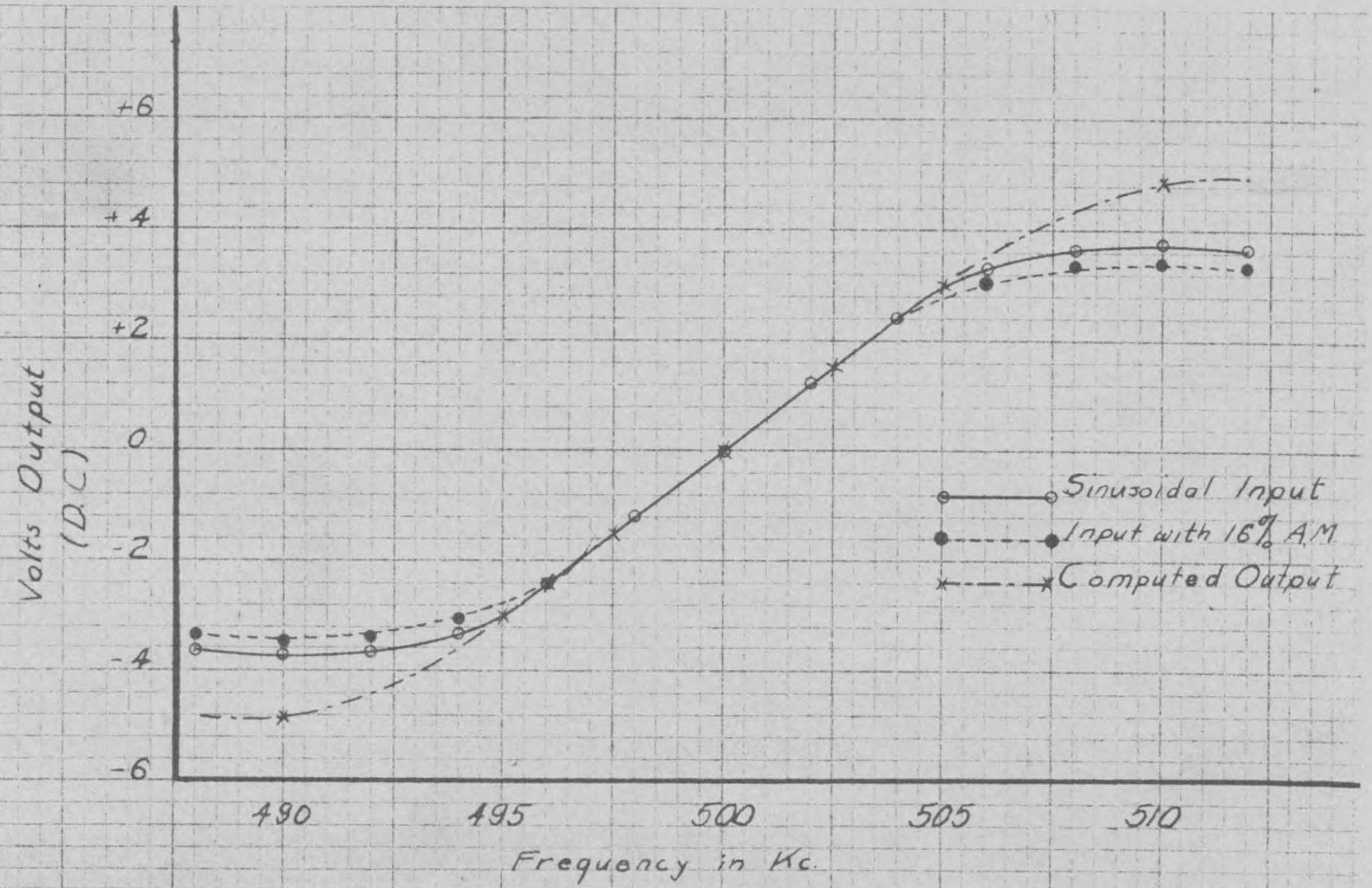
[1] "From 1/3 to at most 2/3 of the peak separation range is normally linear." F. E. Terman, 1943. RADIO ENGINEER'S HANDBOOK. McGraw-Hill Book Co., N. Y., p. 586.



FOSTER-SEELEY DISCRIMINATOR CURVES
FIG. 1

where the subscripts p and s indicate primary and secondary. Hund[1] indicates that the width of a theoretically perfect discriminator would be the above expression with the 0.8 replaced by 1. This work is based on the assumption of critical coupling however, so the result would be high when compared to actual circuits. It would not be likely that commercial discriminators would be designed with critical coupling, since a small error would allow coupling to exceed the critical value with the result that secondary current and voltages would no longer have a single maximum. The double peak of a tightly coupled circuit is not satisfactory for a discriminator transformer, hence it is better to sacrifice a little in band width to insure linear operation in the center part of the response curve.

Fig. 1 shows the effect of introducing amplitude modulated waves rather than the pure sinusoidal wave shape used in the tests described in previous paragraphs. It is observed that in the linear portion of the curve the effect of the addition of AM is negligible. This may be most easily explained on the basis of the components of an AM wave. The expression for the current of such a wave is

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[1] August Hund, 1942. FREQUENCY MODULATION. McGraw-Hill Book Co., N. Y., p. 204.

$$I_t = I_m \sin 6.28\, Ft + 0.5\, K\, I_m \left\{ \sin\left[6.28\,(F + f)\; t\right] + \sin\left[6.28\,(F - f)\; t\right] \right\} \ldots\ldots\; 2.$$

where K is the modulation index.[1] In this form it is seen that the upper and lower side-bands occur at frequencies of (F+f) and (F-f) respectively, and that they are of equal magnitude. This indicates that the net effect on a balanced discriminator will be equivalent to that of a wave of magnitude double that of either side-band and at a frequency midway between them, which is the frequency of the carrier. From this it is seen that in the region where the side-bands do not fall in curved parts of the output characteristics, an amplitude modulated wave will produce the same output as a sinusoidal wave of equal effective value. This is verified by the test data.

Tests of distortion of wave shapes in each discriminator confirmed the results of the linearity test. A signal generator used to produce FM output was connected to the input of the discriminator. The output of the discriminator was then connected through an electronic switch to the vertical deflecting plates of a cathode-ray oscillograph, and to the

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1. This expression is derived from the general equation $I_t = I_m\ (1 + K \cos 6.28\, ft)\ \sin 6.28\, Ft$ by expansion and use of simple trigonometric substitutions.

second channel of the electronic switch was connected the original modulating voltage. This allowed a visual comparison of the original wave and the output from the circuit. With no distortion the waves should be perfectly superimposed and when the magnitude of the modulating voltage was such that the discriminator was driven to a nonlinear part of its operating curve, distortion appeared. The signal generator used had a sensitivity of 3 kc./ volt of modulating signal. To obtain a frequency deviation ± 4 kc., which is the limit of linear operation of this discriminator, the effective value of a-c input signal required was $\frac{4}{3} \times \frac{1}{\sqrt{2}}$ which is 0.942 volts. This voltage gave a reasonably good reproduction of the input wave, but when the input signal was increased to 1.0 volt and above, distortion occurred.

Tests of this part were limited to modulating frequencies of 60 cycles. This low audio frequency made the analysis of the side-band components simple since with very large values of $\frac{\Delta F}{f}$, all significant side-bands may be considered as being contained in a band width twice ΔF[1].

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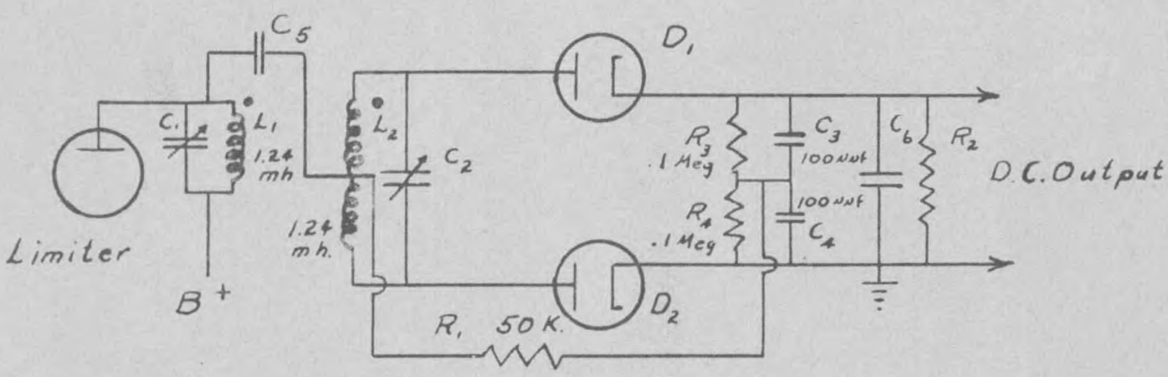
[1] August Hund, 1942. FREQUENCY MODULATION. McGraw-Hill Book Co., N. Y., p. 28.

ANALYSIS OF THE FOSTER-SEELEY CIRCUIT

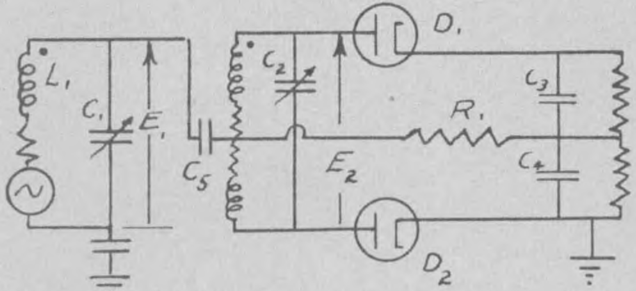
The complete circuit diagram of the laboratory model of this discriminator is shown in Fig. 2-a. For frequencies other than 500 kc. the values of circuit elements would vary somewhat, but most commercial applications of this discriminator use this circuit layout with few modifications. The analysis is on the basis of equivalent circuits, which are given in Fig. 2-b and c. The sketch of Fig. 2-b is essentially the same as the actual diagram, with the limiter replaced by an equivalent generator, and the appropriate by-pass condenser added. The last part of the output filter has also been omitted since it plays no part in the actual operation of the circuit.

Several articles have been written concerning the basic operation of the Foster-Seeley discriminator, and some discrepancies exist as to the relative phase of the voltages in the circuit. It seems desirable therefore, that the complete action be explained so that the experimental data may be confirmed.

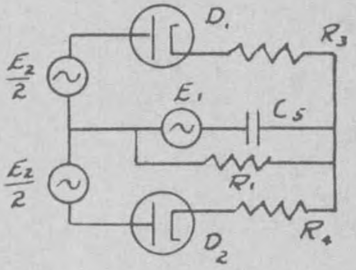
The basic theory of tuned-coupled circuits is completely discussed in several texts. The work of Terman is referred to frequently in the following paragraphs. In almost all cases the equations given are based on a series excitation in the primary side of the circuit, as shown in Fig. 3.



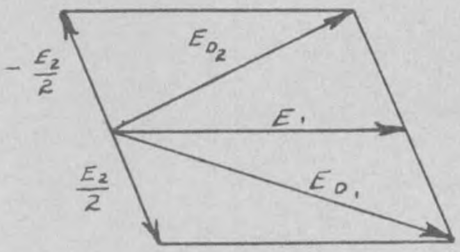
Actual Circuit Diagram
FIG 2- a



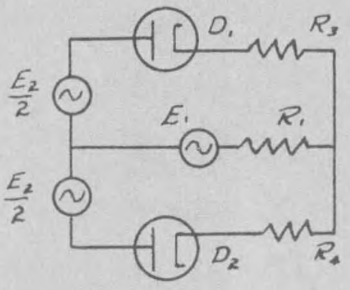
Simplified Diagram
FIG 2-b



Equivalent Diagram
FIG 2- c

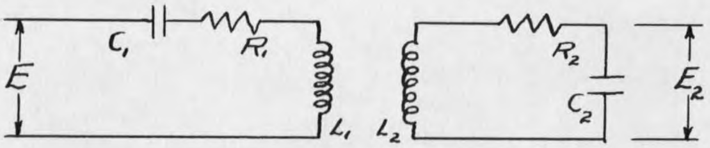


Vector Diagram
FIG 2 - d



Equivalent Circuit
FIG 2- e

FOSTER- SEELEY DISCRIMINATOR
FIG 2



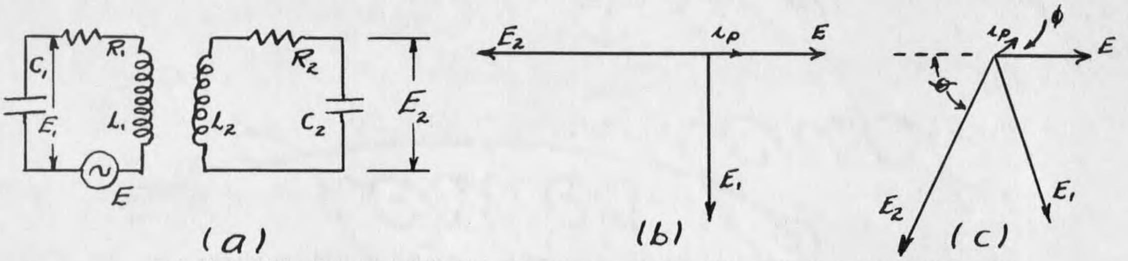
Basic Tuned-Coupled Circuit.
Fig. 3

The equation for the magnitude and phase relations of[1] E_2 to E as shown in Fig. 3 is

$$\frac{\text{voltage across the secondary condenser}}{\text{voltage applied in series with primary}} = \frac{E_2}{E} =$$

$$\frac{-1}{r^2}\sqrt{\frac{L_2}{L_1}}\;\frac{k}{\left[k^2 + \frac{1}{Q_pQ_s} -(1-\frac{1}{r^2}) + j(1-\frac{1}{r^2})(\frac{1}{Q_p} + \frac{1}{Q_s})\right]} \quad .. 3.$$

where $r = \frac{\text{actual frequency}}{\text{resonant frequency}}$, k = coefficient of coupling and Q_p and Q_s are Q's of the primary and secondary coils, respectively. This equation cannot be directly applied to the discriminator to be analyzed since the discriminator is based on a parallel excitation and E_1 is the voltage across the



Voltage relations in Tuned-Coupled Circuits
Fig. 4

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[1] F. E. Terman, 1943. RADIO ENGINEER'S HANDBOOK. McGraw-Hill Book Co., N. Y., p. 155.

condenser C_1. The circuit and vector diagrams of Fig. 4 show the relationship of voltages for the condition of resonanse and for a frequency below the resonant frequency. Fig. 4-a is essentially the same as Fig. 3 with circuit elements rearranged to make comparison with the actual discriminator easier. The voltage E is the driving voltage in the primary coil, and at resonant frequency would lead E_1 by 90° since the current at resonance is in phase with the voltage source, E, and the voltage drop across a condenser is 90° behind the current through it. Voltage E_2 is shown 180° behind E, as was indicated by equation 3. This makes the two voltages E_1 and E_2, used in the discriminator analysis, have a 90° relation as is shown in Fig. 4-b.

As the frequency is reduced below the resonant value, the phase relation between E and E_1 changes slightly as is indicated in Fig. 4-c. This change is small since the Q of the circuit is relatively low. The Q is intentionally made low so that a wide frequency deviation is possible. There is a decided change in the phase relation between E_2 and E, however, as is indicated by equation 3. The value of r in this equation is reduced to less than one, and the phase of the entire expression is such as to make the angle become greater than 180°. This change is a function of r^2 so the phase change indicated as θ on the figure is much greater than the change indicated as ϕ which was discussed above. The net result is to make the angle between E_1 and E_2 less than 90°.

In analyzing the action of the discriminator it is more convenient to use the voltage E_1 as a reference, and this is done in the diagram of Fig. 2-d referred to previously. For frequencies less than the resonant value, the voltage relations are indicated. It is to be observed that the voltages across the diodes are the sum of E_1 and $\frac{E_2}{2}$ since only half of E_2 is effective from either side to the center tap.

The vector diagram indicates that the voltage across diode D_1 is greater than the voltage across diode D_2 and that the output will then be positive as measured from ground to the output terminal. This agrees with the experimental data for the coil polarity as shown.

The computations from which the calculated output curve was obtained were made using the sketch of Fig. 2-e as the circuit. In this part it is to be noted that all the filter elements have been omitted, and that the voltage E_1 is placed in series with R_1. This simplification of Fig. 2-c is possible since the d-c current cannot flow through C_5, the blocking condenser. The a-c current which circulates through E_1, C_5 and R_1 in Fig. 2-c causes the voltage E_1 to appear across R_1 since the reactance of C_5 is small. The final result is the circuit of Fig. 2-e.

The resistors R_3 and R_4 are the load resistors for the two diodes and are 0.1 megohm each. This high value of resistance limits the current flow through the diodes, and makes the voltage loss in the tubes very small. The tubes are assumed to be perfect in the analysis which follows, since the resistance which they present will be negligible compared to the high load resistance.

The resistor R_1, which in some circuits is replaced by a r-f choke, had a resistance of 50,000 ohms in the circuit tested. At radio frequencies the resistance R_1 is effectively in parallel with the resonant primary circuit. This allows E_1 to be effectively across the resistor, and makes analysis possible on the basis of the equivalent circuit shown. Circuits which use a choke for this purpose have an element which has the effect of detuning the primary tank, and also one which had a variable reactance to different frequencies. The possibility of resonance between a choke and capacity C_5 also makes use of a resistor more desirable than use of the choke. The resistor does, of course, reduce the d-c output of the circuit but it is used in many commercial applications despite this limitation.

The limiter holds the input to the discriminator constant, in the case of the circuit tested, to a value of 5 volts. The voltage across the secondary depends upon the coupling between the coils and the turns ratio, as well as the relative Q's of the two coils. For the laboratory model the Q's were measured by the half-impedance points on an impedance frequency curve and in both coils were found to be 22.4.

The circuit analysis which was shown previously indicates that the series voltage applied in the coupled circuit must vary if the voltage E_1 is to remain fixed for all values both above and below the resonant frequency. For approximate analysis the assumption may be made that this variation is such as to hold the voltage E_2 fixed also, provided that the deviation from resonant frequency is small. This is confirmed by the experimental data. With this assumption it is to be seen that the phase angle between E_1 and E_2 is the only variable, and this is a function of the Q of the circuits. Since the Q's of both circuits are the same in this case it is assumed that the phase angle varies with the impedance angle of the secondary circuit, and that the angle between E_1 and E_2 differs from 90°, the angle of resonance, by this impedance angle.

The phase relation between the voltages across diode #1 and diode #2 is not fixed but it is approximately 90° at all times if the magnitudes of E_1 and $\frac{E_2}{2}$ are nearly equal. With this additional fact it is possible to consider the current flow through the two diodes independently. This approximation involves some error due to the complex voltage drop across R_1;

however since R_1 is considerably smaller than the load resistors, the error involved is small.

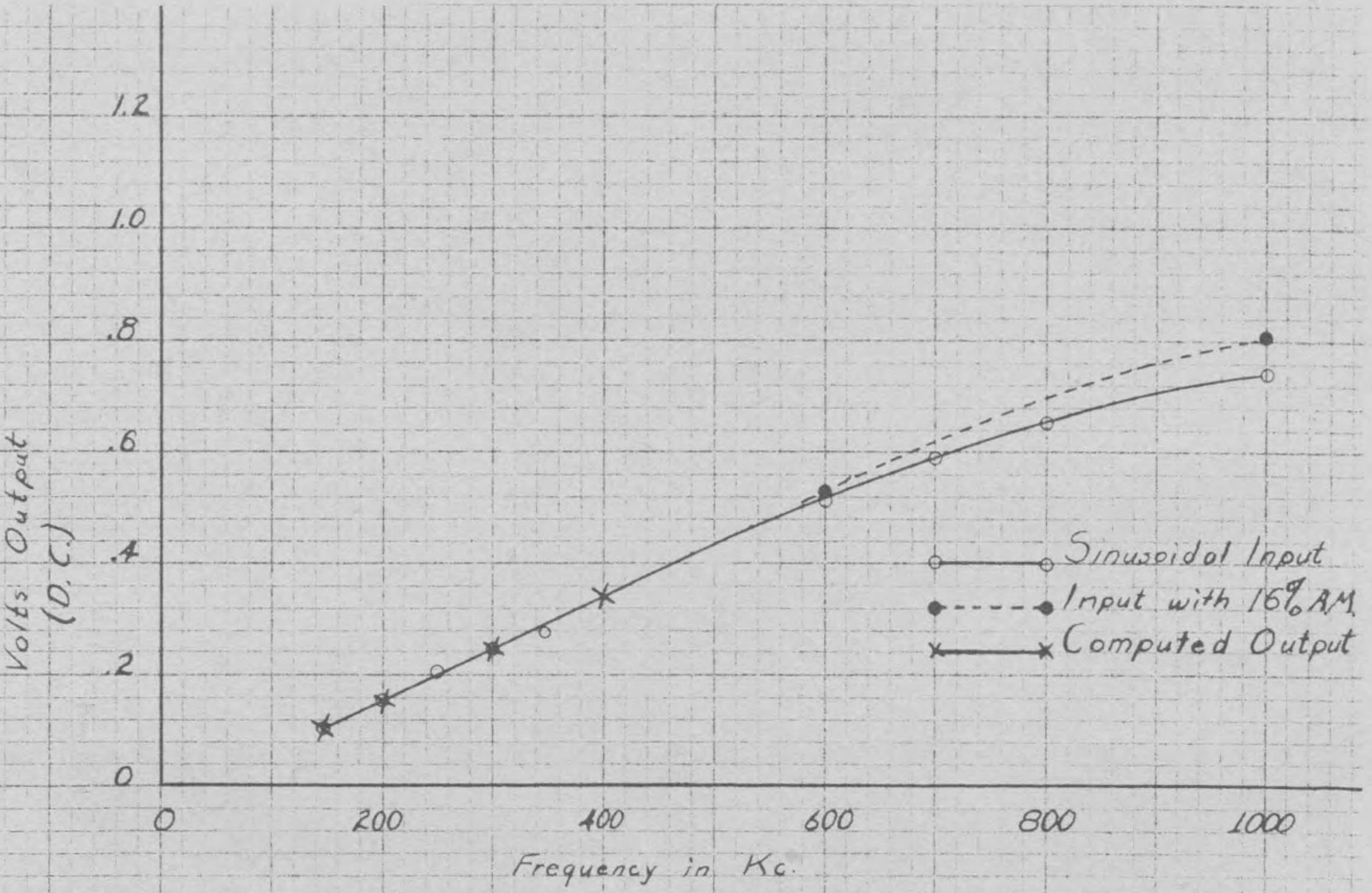
For a specific example of the use of the equations indicated and developed above, the frequency of 495 kc. will be considered, and the actual computations of the output voltage will be shown. The resistance of the secondary coil is assumed constant over the small range of frequencies used in the circuit, and equal to 173 ohms. This value is obtained from knowledge of the Q which is 22.4, the secondary inductance of 1.24 millihenry and the resonant frequency of 500 kc. At 495 kc. the value of X_L is 3855.6 and X_c is 3934.9 ohms. The difference is 79.3 ohms capacitive reactance. The difference involves the fifth significant figure of the original reactances so in problems of this sort slide rule accuracy is not satisfactory, and more exact means of calculation must be used. The secondary series impedance is then $173 - j79.3$ or $190 \underline{/ -24.6^\circ}$. The coefficient of coupling and inductances of the two coils were such that at resonance the primary input voltage of 5 volts produced a voltage of 11.2 volts across C_2. A complete knowledge of coupling and circuit elements would enable one to calculate the ratio from the equations previously given, however in actual circuits it is simpler to measure the ratio.

Using vector addition in the manner indicated in the vector diagram of Fig. 2-d, values of voltages across the diodes are found. E_{d_1} is found to be 8.93 volts and E_{d_2} is 5.75 volts, both effective a-c values. The condensers C_3 and C_4 in parallel with the two load resistors are of size such that they maintain the peak value of the rectified wave effective across the load resistor. The output of the discriminator is essentially into an infinite impedance, namely the grid circuit of an audio amplifier, so the current drain is nearly zero, and the above assumption is justified. The peak values of the two voltages above are equal to the $\sqrt{2}$ times the effective value. The voltage across the load resistor in each case is only $\frac{1}{1.5}$ times the peak value since there is some voltage across R_1. With these additional factors, it is then necessary to multiply the difference between E_{d_1} and E_{d_2} by $\sqrt{2} \times \frac{1}{1.5}$. The result for this particular set of values is 2.99 volts. This agrees well with the value 3.00 volts obtained from experimental data and plotted on the curve. Other values plotted on the curve sheet were obtained in a similar manner.

THE SEELEY-KIMBALL-BARCO DISCRIMINATOR

The discriminator discussed in this section is designated by the names of the three men who developed the system. The circuit is very limited as to the frequency coverage, so has its chief application as a laboratory instrument. It is to be noted in the analysis and discussion which follows that it is possible to limit nonlinearity and distortion to less than 0.5%.

The basic principle upon which the circuit operates is one of charge and discharge of a condenser through resistances. If the ratio of the resistance to capacity is of the correct value, and the time constants of the circuit are carefully controlled, the discriminator has a performance which cannot be equalled in inductively coupled circuits. Fig. 5 shows the experimental and calculated operation curves of the discriminator. Tests were limited to a low frequency of 150 kc. since the signal generators used were limited to that range. There is some curvature in the operating curve at this value however, so there was no necessity of extending the test beyond the value indicated. The experimental curve has appreciable curvature at a value of approximately 550 kc. The calculations in the following section indicate that the actual limitation is at a somewhat lower frequency, but for curves of this size curvature must be appreciable before it



SEELEY-KIMBALL-BARCO DISCRIMINATOR CURVES
FIG 5

is noticeable. A departure from a straight line of at least 1% is possible before it is detectable graphically.

The curve obtained with AM sine waves applied to the discriminator is also plotted on the same figure. In this particular circuit the deviation between this, and the curve obtained with pure sine waves, is small. This is due to the small curvature of operating characteristics even at frequencies very much larger than the maximum permissable value. The calculated values are limited to a frequency range of 150 kc. to 400 kc., since beyond these values deviation from a straight line exceed 0.5%, and for an exact test instrument the circuit is no longer of value.

The high frequency response of the circuit is limited by the time constants of the RC networks as is indicated in the next section of the thesis. The low frequency response is limited by the filter which is connected to the output of the discriminator, and by the nonlinearity of the rectifiers as the frequency is reduced. In the section of this report dealing with diode characteristics it is shown that the effective resistance, which the diode presents, is a function of the d-c current which flows. The voltage loss in the tube becomes excessive below frequencies of about 150 kc., in this circuit, causing the curvature in the low frequency range of operation.

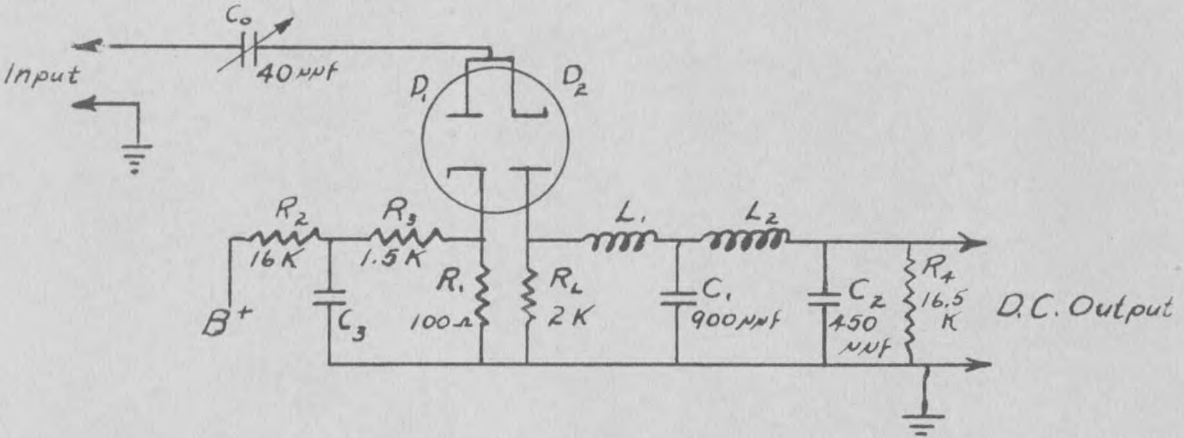
The dependence of this discriminator upon vacuum tubes is a definite disadvantage. Changing tubes would, in general, not cause the operation to be nonlinear; however, it does change the magnitude of voltage obtained from a particular frequency. The calibration of the circuit is very dependent upon the particular tube used. In the tests conducted, four commercial 6H6 tubes were chosen at random from a large stock. Two of those used had glass envelopes and two were metal. The differences in characteristics are shown in the curves of Fig. 9, and the calculations indicate the effect of changing from one to another. Differences in d-c resistance of the tube would change the maximum frequency range of the circuit by increasing or reducing the time constants of the networks. The center range of operating would not be affected other than to uniformly raise or lower the voltage output.

ANALYSIS OF THE SEELEY-KIMBALL-BARCO CIRCUIT

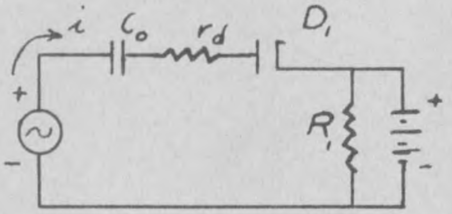
The actual circuit diagram of the laboratory model of this discriminator is shown in Fig. 6-a. The values of circuit elements do not follow the work of the original authors exactly, but the basic operation of the circuit is unchanged. The analysis is based upon the equivalent circuits shown in Fig. 6-b, c and d. The action of the discriminator is broken into three parts. The first to be discussed is the charging of condenser C_o.

The sketch of Fig. 6-b shows the circuit elements effective during the charging period. The input has been replaced by a generator with polarity as shown. During the other half of the cycle, when the polarity reverses, the diode prevents current from flowing, so the circuit is limited to current flow in one direction. The total charge which the condenser C_o gains during a half cycle is the value which must be determined. It is a linear function of frequency, since this is the basis upon which the circuit operates.

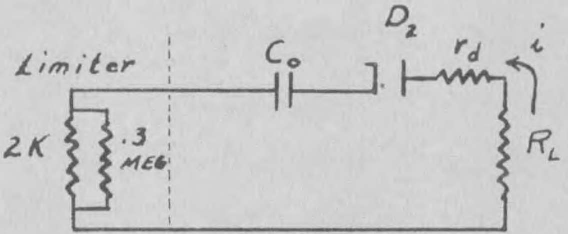
Were it not for the d-c bias on the tube, the solution of the expression for charge would be very simple. This circuit, however, involves both an a-c input and a d-c bias in the series system of rectifier, condenser and resistance. The general expression for voltage drops around the circuit is



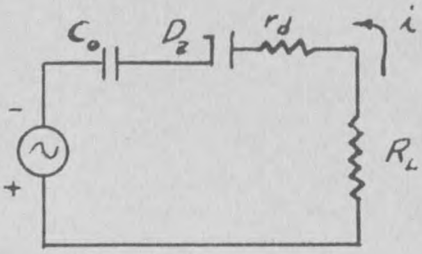
Actual Circuit Diagram
FIG 6 - a



Equivalent Charging Circuit
FIG 6 - b



Equivalent Discharge Circuit
FIG 6 - c



Equivalent Rectifying Circuit
FIG 6 - d

SEELEY - KIMBALL - BARCO DISCRIMINATOR
FIG. 6

$$iR + \frac{1}{C} \int i\,dt = E_m \sin 6.28\,ft - K \quad \ldots\ldots\ldots\ldots\ 4.$$

where K represents the d-c bias, and is negative because its polarity is opposite the instantaneous polarity of the a-c component. By re-writing the expression given above, the equation may be expressed in terms of charge q where $i = \frac{dq}{dt}$.

$$\frac{dq}{dt} + \frac{q}{RC} = \frac{E_m}{R} \sin 6.28ft - \frac{K}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 5.$$

This is a linear differential equation and has an integrating factor of $e^{\frac{t}{RC}}$. When both sides of the equation are multiplied by this factor and integrated, the following is obtained:

$$q = RC^2\ 6.28\ fE_m \left[\frac{\frac{1}{RC\ 6.28\ f} \sin 6.28\ ft - \cos 6.28\ ft}{1 + R^2C^2\ 6.28^2f^2} \right] - KC$$
$$+ K_1\ e^{\frac{-t}{RC}} \quad \ldots\ldots\ 6.$$

Using the well known trigonometric expression

$$a \sin \phi - b \cos \phi = \sqrt{a^2 + b^2}\ \sin (\phi - \tan^{-1} \frac{b}{a})$$

and the additional requirement as is explained in the next paragraph, that $1 \gg 6.28^2f^2C^2R^2$, the equation for q may be simplified and written as

$$q = C \left[E_m \sin (6.28\ ft - \phi) - K \right] + K_1\ e^{\frac{-t}{RC}} \quad \ldots\ldots\ 7.$$

where $\phi = \tan^{-1} RC\ 6.28\ f$

The rectifier limits current flow to one direction so the charge on condenser C_o will reach some maximum value and remain charged, until a discharge path is provided through another part of the circuit. In the previous equations the limitation on useable frequency was placed such that the expression for the charge might be a linear function of frequency. That limitation is given in the expression $1 \gg 6.28^2 f^2 C^2 R^2$. Using the value of C_o of 40 micromicrofarads, and the value of resistance as 100 ohms plus the effective resistance of the diode, it is possible to determine the maximum allowable frequency. With a small load resistance a large current flows through the diode, and the resistance is smaller than the value used in later work with very limited current. A value of 900 ohms is used in this part as a reasonable estimate for an average diode resistance. This value is discussed in the section of this thesis dealing with rectifiers. The total resistance is then 1000 ohms, and when substituted into the expression with the error limited to 0.5%, the maximum frequency is found to be 0.398 mc.

With this limitation it is possible to further simplify the expression of charge. The value of Ø given above is limited to less than 6° and with a d-c bias of 1.4 volts, compared to an a-c signal of 5 volts, the rectification occurs only between approximately 10° and 170° so it is less than a half cycle and the phase angle of 6° is negligible and may be omitted. This limitation of rectification to less than a 180°

interval is the reason for the d-c bias. The constant K_1 may be evaluated by using the boundary condition $q = 0$ when $t = 0$ in equation 7. Therefore

$$K_1 = C\,(\,K + E_m \sin \phi\,) \quad \ldots\ldots \quad 8.$$

The expression for maximum charge is desired, however, and q is a maximum at approximately the time $t = \frac{T}{4}$. Since $(\,K + E_m \sin \phi\,)\,e^{-\frac{T}{4RC}} << (\,E_m - K\,)$ the transient term may be omitted and the expression for maximum charge is

$$Q_m = C\,(\,E_m - K\,) \quad \ldots\ldots \quad 9.$$

The second phase of the operation is concerned with the discharge of condenser C_o through diode D_2 and R_L, the load resistor. The circuit of Fig. 6-c is the equivalent circuit through which the discharge occurs. The limiter is included in this sketch since the discharge must be through the parallel combination of 0.3 megohm and 2000 ohms, which are in the limiter used in the laboratory test. This would differ with the various limiters so analysis must be based upon the individual circuit used.

The discharge is accompanied by a simultaneous recharging of the condenser with the opposite polarity. These two actions are considered separately, however, to simplify the analysis. The theorem of superposition is used, which states that the action of two or more voltage sources in a circuit may be considered individually if the remainder are replaced by their internal impedances. This strictly applies only to bilateral impedances; however, the operation of the entire discharge and rectification is limited to a half period of the incoming frequency, so the rectifier acts as a pure resistance throughout the period considered. The fact that it is not bilateral is therefore of no consequence.

The discharge of a condenser through pure resistances is an action well known to radio engineers. The expression for current is

$$i = \frac{E}{R} e^{\frac{-t}{RC}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 10.$$

where E represents the original voltage across the condenser before discharge begins. To find the average value of current it is necessary to integrate over the time limits during which discharge occurs.

$$I_{ave} = \frac{1}{T}\left[\frac{E}{R} \int_0^{\frac{T}{2}} e^{\frac{-t}{RC}}\right] = \frac{E}{RT} RC \left(1 - e^{\frac{-T}{2RC}}\right) \quad \ldots. \quad 11.$$

To limit error to 0.5% and allow the last term of the above expression to be neglected it is necessary that $e^{\frac{-T}{2RC}} \ll 0.005$. If $\frac{T}{2} = 5.3\ RC$ this is possible, so that a limiting frequency of 471 kc. is found, and since this is larger than is permissable as is indicated in the previous work, the value of I_{ave} is ECF, where F is equal to $\frac{1}{T}$.

The average d-c voltage developed across the load resistor R_L is the product of I_{ave} and resistance R_L. This is therefore, a linear function of frequency.

The second action to be considered during the negative half of the input cycle is that of recharging C_o through a series resistance. This is a comparatively simple action since there is no d-c voltage in the circuit. The circuit is shown in Fig. 6-d. The voltage equation is

$$iR + \frac{1}{C}\int i\,dt = E_m \sin 6.28\,ft \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 12.$$

The solution of this equation is given in any text dealing with a-c circuits.[1] The usual form for the current in this circuit is

$$i = \frac{E_m}{Z} \sin(\,6.28\,ft - \phi\,) + K e^{\frac{-t}{RC}} \quad \ldots\ldots\ldots\ldots\ldots\ldots 13.$$

where $Z = R - j\,\frac{1}{6.28\,fC}$ and $\phi = \tan^{-1} \frac{-1}{RC\,6.28\,f}$

To evaluate the constant K in the above expression the current at time t = 0 must be known. From the preceeding paragraphs the maximum current due to discharge has been found to be $\frac{(E_m - 1.42)}{5000}$. Using this as the value of i when t = 0 the equation may be rewritten as

$$i = \frac{E_m}{Z} \sin(6.28\,ft - \phi) + \left(\frac{E_m}{Z} \sin\phi + I_o\right) e^{\frac{-t}{RC}} \ldots.\ 14.$$

where I_o is the current at time t = 0.

The average voltage developed across the output resistor is

$$E_{ave} = R_L\ \frac{1}{T}\int_0^{\frac{T}{2}} i\,dt$$

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[1] K. Y. Tang, 1940. ALTERNATING CURRENT CIRCUITS. International Textbook Co., Scranton, Pa., p. 395.

$$E_{ave} = \frac{E_m R_L}{Z} \left[\frac{\cos \phi}{3.14} + FRC \left(\sin \phi + \frac{I_o Z}{E_m} \right) \right] \ldots\ldots\ldots\ldots \quad 15.$$

where ϕ is defined above, and R is the total series resistance of the circuit.

To illustrate the evaluation of the actual voltage output at a specific point, consider the frequency $F = 0.3$ mc. The voltage developed across R_o due to discharge of C_o is

$$E_{ave} = ECFR_L = (7.07 - 1.42)\ 40\text{x}10^{-12}\text{x}\ 0.3\text{x}10^{6}\text{x}2000$$

$$= 0.135 \text{ volts.}$$

The voltage developed across R_o due to rectification is

$$E_{ave} = \frac{E_m R_L}{Z} \left[\frac{\cos \phi}{3.14} + FRC \left(\sin \phi + \frac{I_o Z}{E_m} \right) \right]$$

$$Z = R - jX_c = 3000 - j\,\frac{1}{6.28\text{x}0.3\text{x}10^{6}\text{x}40\text{x}10^{-12}}$$

$$= 3000 - j\,13250 = 13600\ \underline{/-77.25^{\circ}}$$

$$E_{ave} = \frac{7.07\text{x}2000}{13600} \left[\frac{\cos(-77.25^{\circ})}{3.14} + 0.3\text{x}10^{6}\text{x}3000\text{x}40\text{x}10^{-12} \text{x}(\ 2.17 + \sin -77.25^{\circ}) \right]$$

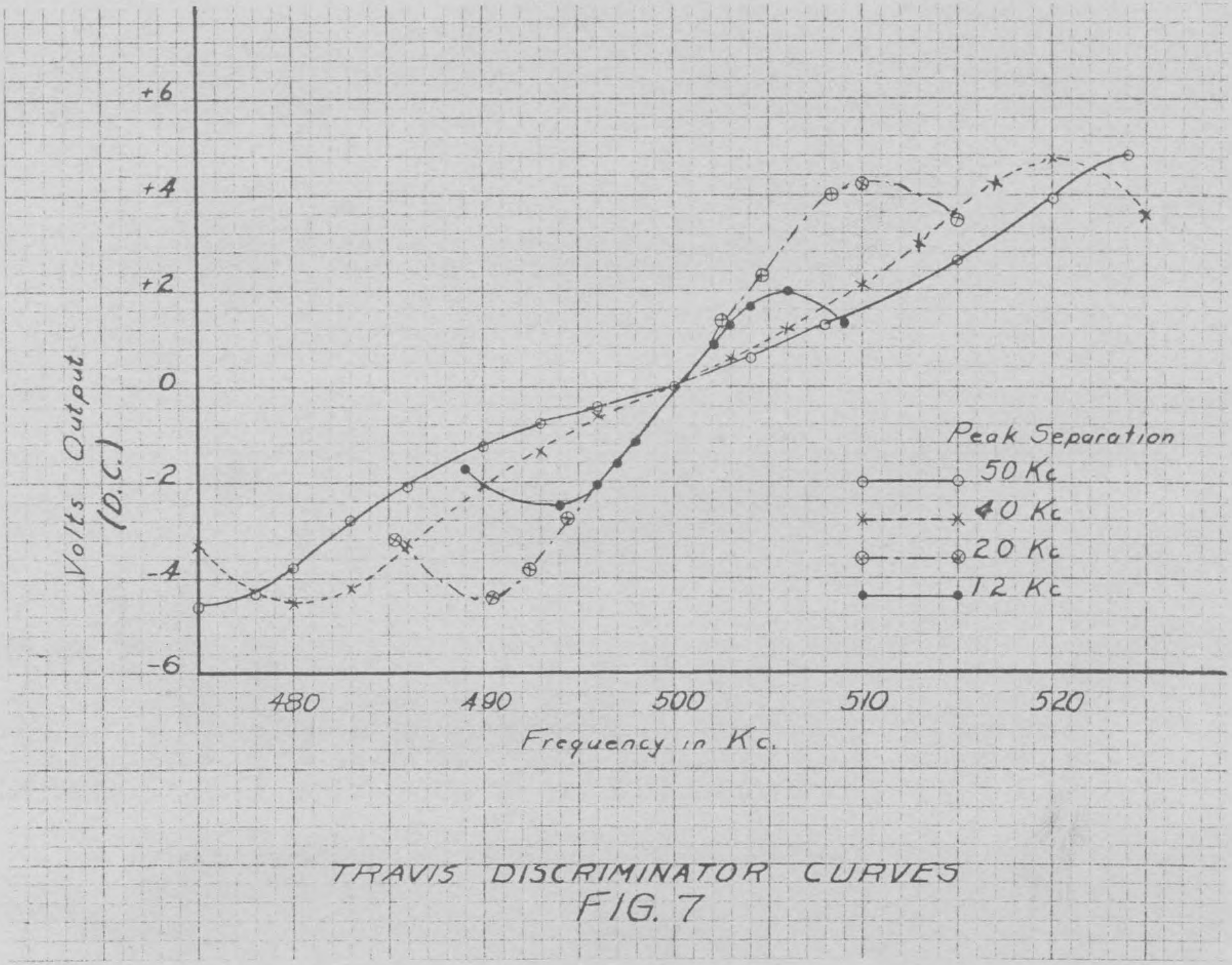
$$= 0.117 \text{ volts.}$$

The total output is the sum of the two voltages computed above, and is 0.252 volts. This compares well with the value 0.25 which was determined experimentally and which is read from the curve. Similar calculations were made for the other points shown on the curves of characteristics for the Seeley-Kimball-Barco discriminator.

THE TRAVIS DISCRIMINATOR

The Travis discriminator is sometimes referred to as the Crosby circuit since both men did development work on the system. The name of Travis seems to be the more widely used of the two, so it will be the name applied to the circuit in this thesis. The basic operation of the circuit depends upon a primary tuned circuit, and two secondary circuits, one of which is tuned slightly above and the other slightly below the primary resonant frequency. The difference in response of the two secondaries gives an output which may be made linear over a fairly wide range if the circuit is properly adjusted.

The tests conducted on this circuit differed slightly from those used on the other discriminators, since the Travis system lends itself to a large number of different settings and adjustments. The first series of tests were conducted to find the relation between linearity and the amount by which the two secondary circuits could be detuned from the primary frequency. The results of these tests are plotted on Fig. 7 in the form of curves of voltage output vs. frequency. The four curves shown are plotted for secondary frequencies of 25, 20, 10 and 6 kc. above and below the primary resonant value. It is to be noted that the first two have appreciable curvature, and would be of no value as a discriminator output. The curve of 10 kc. frequency difference appears to be nearly



TRAVIS DISCRIMINATOR CURVES
FIG. 7

linear on the curve of Fig. 7. However, when plotted to a very much larger scale, with narrow pencil lines for curves, it is seen that there is some small curvature of the same general type found in the two curves previously discussed. The curve with 6 kc. frequency difference is linear within the limits of accuracy of plotted results.

Using the curve with 12 kc. peak separation as the maximum band width permissable, the useable portion of the curve appears to be approximately ±4.0 kc. with respect to the center frequency. This again was determined from a larger, more carefully plotted, curve.

Travis[1] has indicated that the maximum separation of peaks of voltage output is given by the empirical expression $\frac{F_o}{Q_p}$, where F_o is the primary resonant frequency and Q_p is the Q of the primary tank circuit. This agrees well with the results obtained from the experimental work, and with the graphical analysis which follows in the next section. With a center frequency of 500 kc, and a primary Q of 38.0, the peak separation should be 13.1, according to Travis. This value does not give the useable part of the curve, however, but merely the separation between the points of maximum voltage.

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[1] Charles Travis, "Automatic Frequency Control", PROC. I. R. E. 23 (1935), p. 1130.

output. The useable part of this range is approximately 2/3 of this band, somewhat more than in the case of the Foster-Seeley circuit.

The chief advantage of the Travis system is that it is possible to obtain a high sensitivity, volts/kc., with the proper adjustment. In general the narrower the peak separation, the greater will be the sensitivity. The limit of this increase will be at the point that the linearity is lost due to the curvature at the peak of the resonant curve. This will be explained in the next article. Travis, in the article cited previously, states that the maximum sensitivity occurs when the peaks of output are separated approximately $\frac{\sqrt{2}}{4}\frac{F_o}{Q_p}$.

An empirical design equation has been developed by Roder which gives the useable band width as a function of the Q of the primary network and the resonant frequency. This equation is[1]

$$Q_p = \frac{F_o}{1.5\,W} \qquad \text{..} \qquad 16.$$

where Q_p is the Q of the primary network, W is the band width and F_o is the primary resonant frequency. This formula takes into account the fact that not all of the curve is linear, so

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[1] Hans Roder, "Theory of the Discriminator Circuit for Automatic Frequency Control", PROC. I. R. E. 26 (1938), p. 590.

that the value of W as determined is the useable part of the entire curve.

Applying this equation to the circuit tested in the laboratory to determine W, the value of Q of 38.0 and the resonant frequency of 500 kc., gave a W equal to 8.77 kc. This agrees fairly well with the band width determined by test.

The effect of an amplitude modulated wave being used for input, instead of the pure sine wave, is the same as in the case of the Foster-Seeley circuit. In the band of frequencies where both side-bands of the AM wave fall in the linear part of the discriminator operating curve, the output is the same as if a pure sine wave of the same effective value is used. When the side-bands fall in the curved part of the operating range of the discriminator, the output of the discriminator is reduced, as was explained in the discussion of the Foster-Seeley circuit.

ANALYSIS OF THE TRAVIS CIRCUIT

The complete circuit diagram of the laboratory model of this discriminator is shown in Fig. 8-a. The frequency used for the primary was 500 kc., the same as in the case of the Foster-Seeley circuit. The primary resonant circuit was paralleled by resistor R_1, in this case 0.1 megohm. This was to broaden the response of the circuit, or to reduce the Q. The measured value of Q of the primary branch was 38.0, which is about half the Q of the secondary circuits.

The load resistors R_4 and R_5 tend to load the secondary resonant circuits also, and to broaden their response. Roder[1] has shown that the resistance effectively in parallel with the tuned circuit is $\frac{R_L}{2}$ where R_L represents the load resistance coupled through a half-wave rectifier. This is illustrated in Fig. 8-b. The parallel resistance is then 50,000 ohms in the case of each of the secondary coils, and the one-half ratio of Q's indicated above is confirmed.

The signal voltage is supplied to this circuit in parallel with the tuned primary of the transformer as was the case in the Foster-Seeley circuit. The limiter stage which normally preceeds the discriminator in any application has the

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1. Hans Roder, "Theory of Discriminator Circuits for Automatic Frequency Control", PROC. I. R. E. 26, (1938), p. 594.

effect of holding the voltage across the condenser C_1 fixed. This means that the voltage considered in series with the LC combination must vary, and similarily the voltage induced into each of the secondary coils varies. The final effect depends upon the degree of coupling of the circuits, and the relative values of Q. In the case of the particular circuit tested, the voltage developed across load resistors R_4 and R_5 acts as though the effective Q of the circuit was approximately 36.0. This is very slightly less than the Q of the primary network.

Analysis of the Travis circuit is most easily made on the basis of a graphical addition of the output voltages of the two secondary circuits. This is illustrated by Fig. 8-d.

Terman shows that the curve of current in the secondary of a double-tuned-coupled circuit has the same shape as the curve of current in the primary of the resonant network[1], with a Q which is higher than the Q of either the primary or the secondary branches. The Q of the circuit of this discriminator has already been discussed, but the fact that the current is approximately a resonant function is of some help in the analysis. The universal resonance curves given by Terman[2] may

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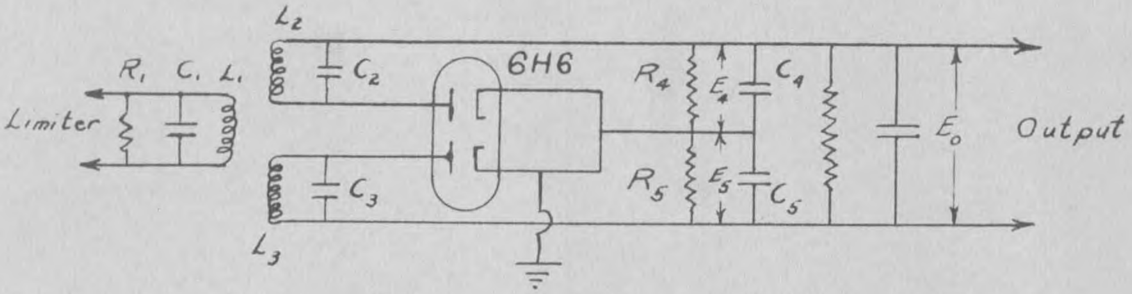
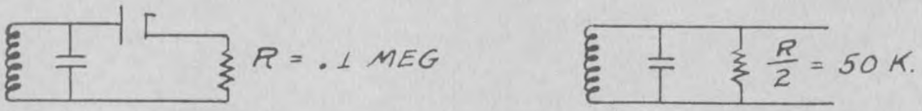
[1] F. E. Terman, 1943. RADIO ENGINEER'S HANDBOOK. McGraw-Hill Book Co., N. Y., p. 152.

[2] F. E. Terman, 1937. RADIO ENGINEERING. McGraw-Hill Book Co., N. Y., p. 56.



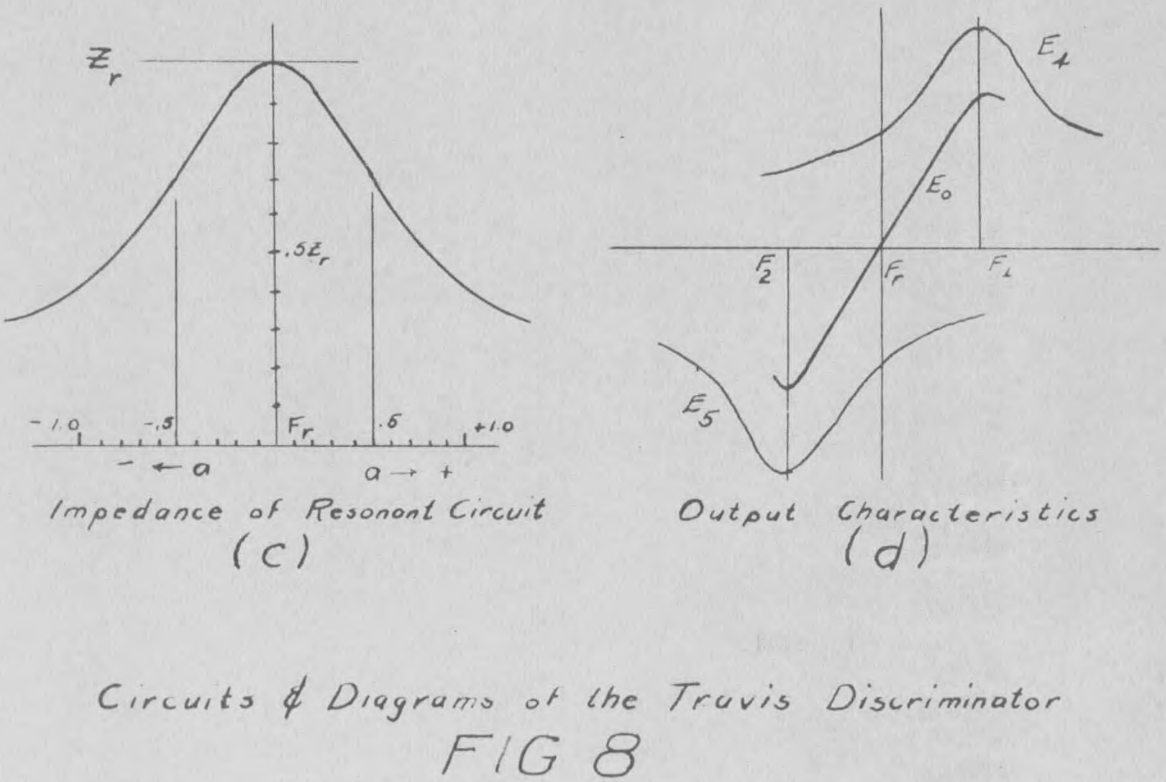
Actual Circuit Diagram

(a)



Effect of Diode Loading

(b)



Impedance of Resonant Circuit

(c)

Output Characteristics

(d)

Circuits & Diagrams of the Travis Discriminator

FIG 8

be used to predict operating characteristics of the circuit. The curves referred to are merely a graphical way of quickly determining the ratio of impedance at any frequency to the impedance at resonance. If the Q of the circuit to be analyzed is greater than 10, the error involved in using the universal curve is negligible.

The impedance of a parallel resonant circuit may be written as $R_{eq} + jX_{eq}$ where the value of X_{eq} may be inductive or capacitive, depending whether the frequency is below or above resonance. It can be shown that a plot of equivalent resistance vs. frequency gives a curve similar in shape to the curve of total impedance, except that the resistance curve is much sharper and narrower. The resistance is equal to the reactance, and each is equal to ½ the resonant impedance when the frequency is such that "a" is equal to 0.5 where

$$a = Q\,\frac{\text{Cycles off resonance}}{\text{Resonance frequency}}$$

At this point the reactance is a maximum, and as the value of a is increased, the reactance reduces very rapidly. This is discussed by Terman[1].

This discussion indicates that the universal resonance

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[1] F. E. Terman, 1943. RADIO ENGINEER'S HANDBOOK. McGraw-Hill Book Co., N. Y., p. 145.

curve has a change of curvature at a point where a is equal to 0.5 The sketch of Fig. 8-c indicates this point graphically. If the addition of the two response curves is to be made as indicated in the sketch of Fig. 8-d, the resulting curve can be linear only when there is a single direction of curvature in the portions to be added. This limits the separation of frequencies F_1 and F_2 to a value of 2a.

The peak separation is then twice the "cycles off resonance" and is equal to $2 \times 0.5 \times F_r \frac{1}{Q}$ or

$$\text{peak separation} = \frac{F_r}{Q}$$

which agrees with the results predicted by Travis.[1]

The fact that the Q's of the secondary networks are made equal to twice the Q of the primary tank, and that the Q of the primary tank is intentionally made very low, makes the effective Q of the entire secondary network, including tube and load resistance, approximately equal to the Q of the primary. In the case of the laboratory model the ratio was 36/38, which is nearly unity.

The spacing between secondary resonant frequencies may be reduced below the value indicated above. A reduction of this spacing will increase the sensitivity of the circuit at

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[1] Charles Travis, "Automatic Frequency Control", PROC. I. R. E. <u>23</u>, (1935), p. 1130.

the expense of band-width. The minimum spacing is limited by the curvature at the peak of the resonant curve, where there is a reverse in curvature. This is approximately at a point where a = 0.2 . Travis developed an expression which agrees fairly well with this value. This was discussed in the previous section.

In the work on this circuit the accuracy is not nearly as good as in the case of the two circuits previously discussed. A graphical analysis is more restricted than a mathematical one however, so these differences are to be expected. Much of the work previously done on the Travis discriminator has been of an empirical nature, since a detailed rigorous derivation of current and voltage expressions has proved to be rather involved, and the empirical and graphical results have proved satisfactory.

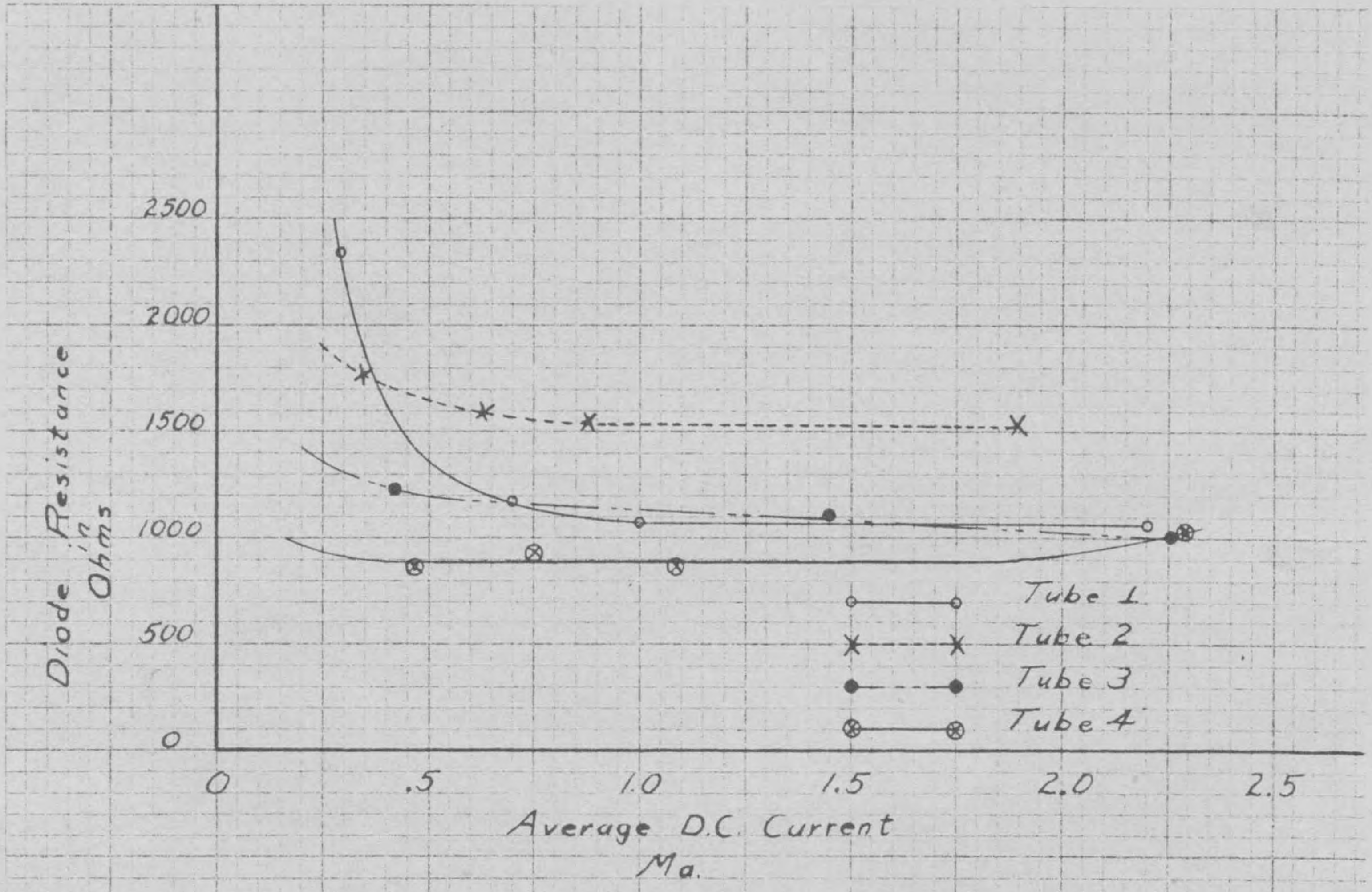
DIODE CHARACTERISTICS

The diode rectifier is such an important part of the discriminator that it was necessary to briefly study the characteristics of the tube in order that a complete analysis of the discriminator circuits could be made. The effective resistance of a diode is the most important characteristic that need be known for this work.

In the appendix of this thesis an equivalent circuit of a rectifier and its load resistance together with the equivalent plate resistance of the diode is found. The losses in a diode may be considered in several ways. The most convenient method for this work was to consider the tube to be a perfect rectifier, without losses, in series with a resistance which is considered to be in the tube. On this basis it is shown in the appendix that the equivalent resistance is

$$r_d = \left[\frac{0.451\ E_{eff} - E_L}{E_L}\right] R_L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 17.$$

where r_d is the resistance of the diode, E_{eff} is the effective value of the a-c input voltage, and E_L is the d-c voltage measured across the load resistance. This equation was applied to a series of test values on the four rectifiers used in the work of this thesis. The curves of Fig. 9 show the resistance as a function of the average d-c current through the



DIODE RESISTANCE
FIG 9

load resistor. The measurements for this test were all made with a load resistance of 2000 ohms, which is the load resistance of the Seeley-Kimball-Sarco discriminator. The effective tube resistance would vary somewhat with different values of load, but the comparison would be constant.

Tubes for this test were chosen at random from a large stock of commercial 6H6 rectifiers. To obtain as general a selection as possible, two of those used were glass and two were metal. The tubes represented the work of different manufacturers, also. There is a fair degree of uniformity between tubes 1, 3 and 4, but tube 2 had a comparatively large resistance. This may have been due to variations in manufacture, or could have resulted from long periods of use. As a tube is used, the emission tends to be reduced until it is finally of no further value. Although tube 2 had been used several hours, when tested with a commercial tube tester it was found to be satisfactory. These curves show the variation which may be found in tubes and give an indication of the allowances which must be made in design of circuits, so that satisfactory operation will result with any of the tubes manufactured under the same identifying number.

An average tube resistance of 1000 ohms was used in the discharge circuit of the Seeley-Kimball-Sarco discriminator since the resistance of the load was the same as the value used in the test for curves of Fig. 9. For the charging circuit a value of tube resistance of 900 ohms was used, since the load resistance was only 100 ohms. For the same input signal voltage it would be reasonable to choose a lower diode resistance, since as is indicated by the curves, the tube resistance reduces as the current increases. This will not continue indefinitely, of course, since the emission of the tube has a very definite limit, and further increase of current will cause the resistance offered by the tube to increase at a very rapid rate. In the case of the 6H6, the maximum rated d-c current per plate is 4 milliamperes. In most applications the current through the tube is limited to values little greater than 2 milliamperes in order to avoid the possibility of saturation.

For the Travis and Foster-Seeley circuits the resistance of the tube is of little importance. Curves of operating characteristics of the 6H6 tube, available commercially, indicate that the output voltage developed across the load resistor is approximately the peak value of the input signal. This is, of course, based on a capacity input filter, and a load resistance of 0.1 megohm or larger. Experimental data confirms this information. For this reason the tube resistance has been neglected in analysis of circuits involving very large load resistances.

The interelectrode capacities of the tube have been neglected throughout the work of this thesis. The low frequencies used made the reactances of these capacities so large as to be of no concern. The capacity from plate to cathode for a 6H6 would not exceed 4 micromicrofarads. At 500 kc. the reactance of this capacity is 79,500 ohms. In parallel with the diode resistance of approximately 1000 ohms, this reactance has no effect. The capacity between the two diode sections in the same envelope is even smaller, approximately 0.1 micromicrofarad.

For discriminators in late model FM receivers with intermediate frequencies of 10.7 mc., tube capacities have considerable effect and must be considered in analysis.

SUMMARY

Discriminators have a variety of uses, chief among which are the detection of frequency and phase modulated waves, automatic frequency control, and calibration of frequency and phase modulation equipment. With these varied uses it is not possible to say that one type of a discriminator is better than another without specifying the purpose for which the comparison is made. Table I gives a tabular comparison of the three circuits studied.

For FM detection the Foster-Seeley circuit, or its more recent modification called the "ratio-detector" is best suited. The chief reason for this is the ease of adjustment of the circuit, and the good stability with change of temperature, supply voltage and tubes. The design of a circuit used commercially must be such that a service-man, with comparatively little technical knowledge, can adjust it satisfactorily and that such an adjustment will be comparatively permanent.

For automatic frequency control the Travis circuit is somewhat better suited, provided maintenance will be done by trained personnel. In general it is possible to obtain greater sensitivity (output volts per cycle of frequency deviation) from the Travis circuit than from others. The Travis circuit is difficult to adjust, and is more subject to mechanical shock and temperature change than is the Foster-Seeley circuit.

TABLE I

COMPARISON OF DISCRIMINATORS

Basis of comparison	Travis Discriminator	Foster-Seeley Discriminator	Seeley-Kimball-Barco Discriminator
Linearity	Good	Good	Excellent
Distortion	Small	Small	Negligible
Maximum Band-width	$\frac{0.67\ F_o}{Q_p}$	*$\frac{0.4 \times F_o}{\sqrt{Q_p\ Q_s}}$	About 250 kc.
Sensitivity (Volts/cycle)	High (Can be varied slightly)	Medium	Very low
Stability (Temperature and mechanical shock)	Good	Excellent	Excellent
Dependence on tube constants	Small	Small	Very dependent
Ease of adjustment	Difficult	Quite simple	No adjustment necessary
Versatility	Excellent	Excellent	Poor

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* Hund (1943) indicates that this value can be nearly doubled if critical coupling is used. This increases the peaks of voltage response separation and allows approximately ½ of the entire curve for operation.

The reason is, of course, that the Travis system requires adjustment of three tuned circuits, each to a different frequency. If coupling between coils is small the adjustments are nearly independent; however there is a tendency in any such circuit for adjustment of one part to be reflected into the others, so the final adjustment is a trial and error process.

For a very high degree of linearity the Seeley-Kimball-Barco circuit is the most desirable. The low center frequency to which this circuit is limited restricts its use for many purposes. The chief application is probably as a laboratory instrument where it may be used to check linearity of various frequency and phase modulating devices such as reactance-tube modulators. The designers of the circuit state that it should be possible to build the discriminator so that linearity of less than 0.02% error can be obtained over a small range of frequencies. The modifications used for the model tested raise this figure to about 0.5%, however a very much greater frequency range is obtained.

The Seeley-Kimball-Barco circuit is very dependent upon tube constants; however with tube change a new calibration curve could be obtained and the stability would be good until it was again necessary to change tubes.

Comparison on other bases are indicated in Table I.

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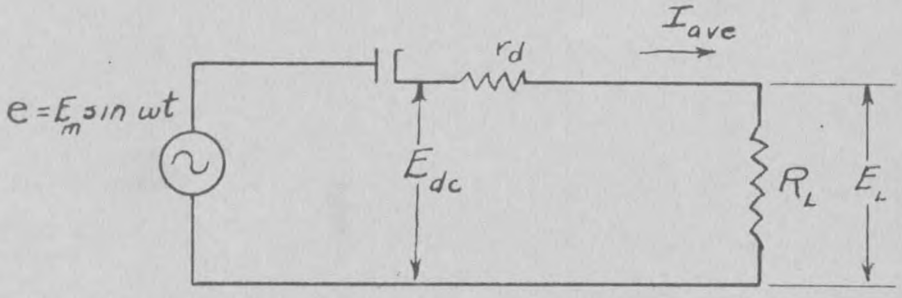
APPENDIX

The plate which follows was not considered to be of such importance to the discussion in the article concerning rectifiers that it was necessary to include it in the text at that point. The derivation of the expression for equivalent diode resistance is not complex, but since the expression used here is not a standard electrical equation, its derivation is included on the next sheet.

APPENDIX



On the basis of a perfect diode

$$E_{dc} = \frac{1}{2\pi} \int_0^{\pi} E_m \sin \alpha \, d\alpha$$

$$= \frac{E_m}{\pi} = .319 \, E_m$$

$$I_{ave} \left(R_L + r_d \right) = E_{dc} = .319 \, E_m$$

$$E_m = \sqrt{2} \; E_{eff}$$

E_L is dc output voltage

$$E_L = I_{Ave} \, R_L$$

$$\frac{E_L}{R_L} \left(R_L + r_d \right) = \sqrt{2} \times .319 \, E_{eff}$$

$$r_d = \left(\frac{.451 \, E_{eff} - E_L}{E_L} \right) R_L$$

This analysis assumes a perfect diode in series with a tube resistance "r_d".