FREQUENCY STABILIZATION OF FREQUENCY MODULATION TRANSMITTER WITH FEEDBACK

Thesis for the Degree of M. S.
MICHIGAN STATE COLLEGE

Edward Frank Vidro, Jr.

1947

This is to certify that the

thesis entitled

"Frequency Stabilization of a
Frequency Modulated Transmitter
with Feedback"

presented by

Edward F. Vicro, Jr.

has been accepted towards fulfillment
of the requirements for

M.S. degree in Electrical Eng.

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Major professor

Date May 20, 1947

M-795

FREQUENCY STABILIZATION OF FREQUENCY MODULATION TRANSMITTER WITH FEEDBACK

by

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A THESIS

Submitted to the Graduate School of Michigan State College of Agriculture and Applied Science in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

Department of Electrical Engineering

1947

THESIS

ACKNOWLEDGEMENT

The author wishes to express his appreciation to Dr. J.A. Strelzoff for his aid in the development of this thesis; and to Professor B.K. Osborn and Professor L.S. Foltz for their suggestion in correcting the manuscript.

E.F.V.

NOTE

The purpose of this thesis was to investigate the problem of frequency stability using the frequency discriminator method of feedback and check certain statements made by Mr. Marchand in his article <u>Direct FM Frequency Control Methods</u> concerning this method.

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FREQUENCY STABILIZATION OF FREQUENCY MODULATION TRANSMITTER WITH FEEDBACK

INTRODUCTION:

The recent increase in commercial frequency modulation stations throughout the country has made the allotment of frequencies closer together. To prevent the overlapping or interference of two transmitters in the same locality, a method of stabilizing the transmitters is required.

Amplitude modulated transmitters and frequency modulation by the Armstrong method do not require special circuits for carrier frequency stabilization. The carrier frequency is stabilized by the use of a piezoelectric crystal oscillator for its generation and the modulation is applied in some later stage of radio frequency amplication. Thus, if the crystal is kept at a constant temperature, the frequency drift will be zero and the carrier frequency will remain constant.

The problem of stabilizing the carrier oscillator in frequency modulation transmitters that use the reactance tube principal for modulation of the carrier frequency is more complicated. The carrier oscillator is caused to deviate from its normal oscillating frequency by the injection of a reactance into the oscillator tank from the reactance tube. The amount the oscillator deviates

is proportional to the modulating voltage input to the reactance tube modulator. Thus the main oscillator shifts frequency upon the application of modulation but it does not necessarily return to its original frequency before modulation. The most common cause of change in frequency of the oscillator is due to the slow drift of the master oscillator because of temperature and voltage changes.

Two methods of stabilizing the carrier frequency will be presented, one is mechanical and the other electrical. The mechanical method will be discussed in this writing only from the standpoint of interest.

A frequency modulated transmitter employing the electromechanical method(1) of center frequency control was built by Western Electric Company, Figure 1 page 3. A system of cascade frequency division is used to reduce the final frequency to that of the crystal oscillator and introduced to two pairs of grids, both pairs being in a push-pull vacuum tube circuit. Each pair of grids is biased negatively by the battery E_c. In series with this bias voltage is a voltage E_{p1} from the crystal oscillator which is applied to one pair of grids, while a voltage E_{p2} of the same magnitude but 90 degrees out of phase with that of the first is applied to the other pair of grids. The voltages E_{p1} and E_{p2} are introduced so that

(1) Hund, August; Frequency Modulation, New York: McGraw-Hill Book Company, Inc.; pp. 241-245; 1942.

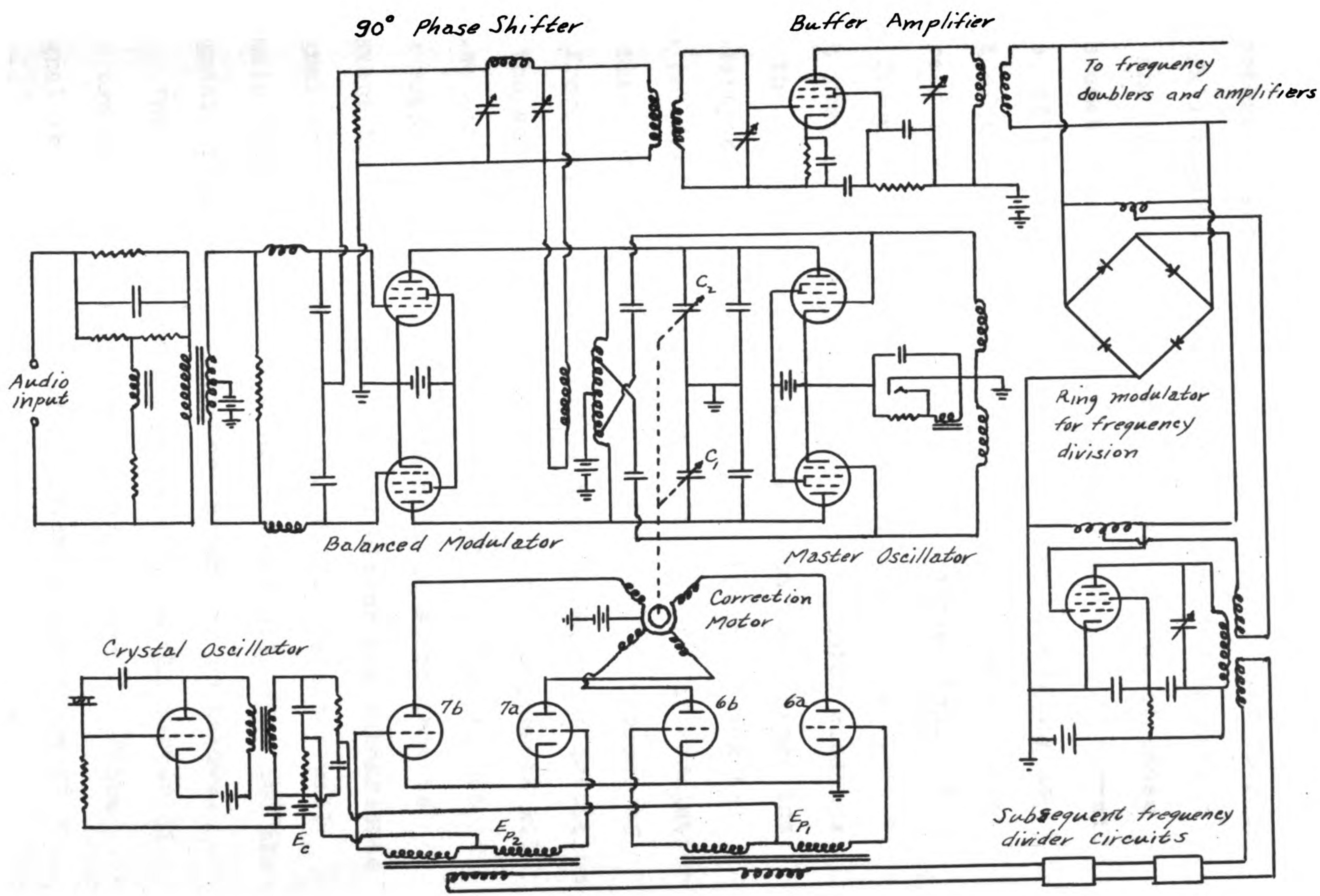

Figure 1. Western Electric Stabilization Method

the grids of the tubes 6a and 7a rise and fall together in potential and similarily the grids of 6b and 7b rise and fall together. Yet, the two grids of each pair (6a and 6b or 7a and 7b) are 180 degrees out of phase with each other with respect to the subharmonic signal. Thus, if the subharmonic is of the same frequency as that of the crystal, there will be zero beat and zero current in the motor windings and no correction. If the frequency is not that of the crystal oscillator, a beat frequency current will flow in the motor windings and the motor armature will rotate and thus change the capacity of the main oscillator resetting it back to the original carrier frequency. The effect of modulation on this method is negligible because of the process of of frequency division which in turn reduces the deviation by the same amount. The remaining audio components will cause the rotor to oscillate at their frequency, but if the rotor is large its inertia will be sufficient to prevent the oscillations. Should either the subharmonic signal or the crystal oscillator fail, the rotor will remain fixed, because only one current will flow and the magnetic field merely pulsates, producing no torque.

The electronic method appears to be the better of the two methods. In general, a small portion of the signal is picked up from some intermediate stage of amplication and returned to the signal grid of a converter tube and beat with the output of a crystal oscillator to a lower discriminator frequency, Figure 2.

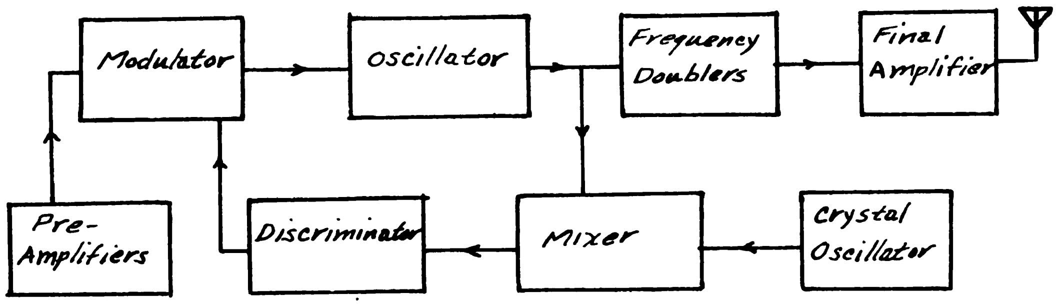

Figure 2. Electronic stabilization system.

The audio components of the discriminator output are bypassed to ground while the direct current component is applied to the control grid of the reactance tube modulator. The output characteristic of the discriminator stage is such that at center frequency of the discriminator transformer, the output voltage is zero. As the frequency of the transmitter drifts from its original value, the beat frequency is higher or lower than the center frequency of the discriminator, thus causing a plus or minus voltage output. This direct voltage when applied to the control grid of the reactance tube modulator changes the mutual conductance of the tube. This change in transconductance changes the value of the injected reactance to the main oscillator tank and returns the main oscillator to its original frequency before the drift.

THEORY AND MATHEMATICS:

The purpose of the reactance tube is to inject a reactance into the associated network, the oscillator tank circuit. The reactance tube and its equivalent circuit are shown in Figure 3.

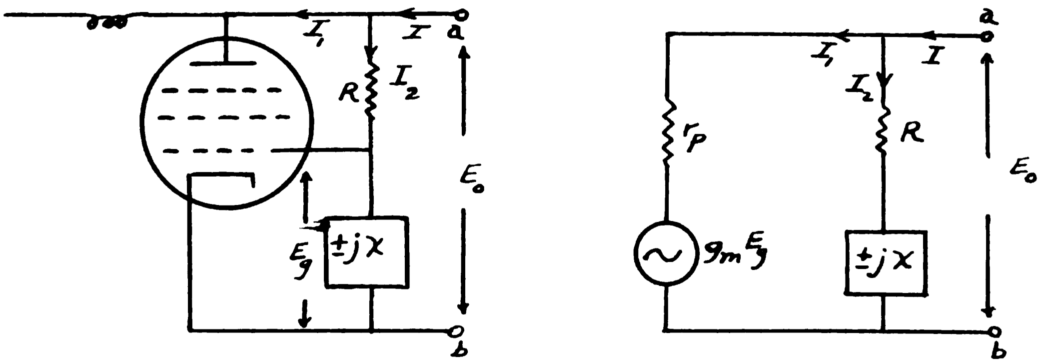

Figure 3.

The impedance that will appear at the terminals a-b of the reactance tube modulator may be found as follows:

$$Z_{ab} = \frac{E_o}{I}$$

$$I = I_1 + I_2$$

$$I_1 = g_m E_g + \frac{E_o}{r_p}$$

$$I_2 = \frac{E_o}{R \pm jX}$$

$$E_g = I_2 (\pm jX) = \frac{\pm jX\, E_o}{R \pm jX}$$

Substituting

$$Z_{ab} = \frac{E_o}{I_1 + I_2} = \frac{E_o}{g_m E_g + \frac{E_o}{r_p} + \frac{E_o}{R \pm jX}}$$

$$= \frac{E_o}{g_m \frac{\pm jXE_o}{R \pm jX} + \frac{E_o}{r_p} + \frac{E_o}{R \pm jX}}$$

$$= \frac{r_p\ (R \pm jX)}{g_m(\pm jX)\ r_p + (R \pm jX) + r_p}$$

$$= \frac{r_p\ (R \pm jX)}{R + r_p \pm jX(1 + g_m r_p)}$$

$$= \frac{r_p R^2 + r_p R + X^2 r_p (1 + g_m r_p)}{(R + r_p)^2 + X^2(1 + g_m r_p)^2}$$

$$\frac{\pm j(r_p + R)Xr_p \mp jXr_p R(1 + g_m r_p)}{(R + r_p)^2 + X^2(1 + g_m r_p)^2}$$

$$Z_{ab} = \frac{r_p\left[R^2 + r_p R + X^2(1 + g_m r_p)\right]}{(R + r_p)^2 + X^2(1 + g_m r_p)^2}$$

$$\frac{\pm j(Xr_p R + Xr_p^2 - Xr_p R - g_m X^2 r_p{}^2 R)}{(R + r_p)^2 + X^2(1 + g_m r_p)^2}$$

$$Z_{ab} = \frac{r_p\left[R^2 + r_p R + X^2(1 + g_m r_p)\right] \pm jXr_p{}^2(1 - g_m R)}{(R + r_p)^2 + X^2(1 + g_m r_p)^2}$$

The mathematical notation for inductive and capacitive reactances is indicated by plus and minus signs respectively. Since in most practical applications $g_m R > 1$, the type of reactance presented across the terminals a-b will be of opposite sign to that reactance in the grid circuit.

$$Z_{ab} = \frac{R^2 r_p + R r_p^2 + X^2 r_p + g_m X^2 r_p^2 \pm jX r_p^2 (1 - g_m R)}{R^2 + 2 r_p R + r_p^2 + X^2 + 2 g_m X^2 r_p + X^2 g_m^2 r_p^2}$$

Assuming a large value for r_p as in the case of multiple grid tubes, then

$$Z_{ab} = \frac{R + g_m X^2 \pm jX(1 - g_m R)}{1 + X^2 g_m^2}$$

For proper design(2) $R \geqq 5X$

and $g_m R \gg 1$, $g_m^2 X^2 \gg 1$ and $g_m X^2 >> R$;

then

$$Z_{ab} = \frac{X^2 g_m \mp j g_m R X}{X^2 g_m^2} = \frac{1}{g_m} \mp j \frac{R}{X g_m}$$

$X_{ab} = \dfrac{\mp R}{X g_m}$ and if X is capacitive,

Then:

$$X_{ab} = \frac{R \omega C}{g_m}$$

Thus an effective inductance is injected at the point

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(2) Ibid. p. 166.

a-b of the value

$$L_{ab} = \frac{RC}{g_m}$$

The effective inductance of the oscillator tank will be

$$\frac{1}{L_{eff}} = \frac{1}{L} + \frac{1}{L_{ab}}$$

as the injected inductance is in parallel with the oscillator tank inductance.

$$L_{eff} = \frac{L\,L_{ab}}{L + L_{ab}} = \frac{\frac{RC}{g_m}\,L}{\frac{RC}{g_m} + L} = \frac{RCL}{g_m L + RC}$$

and as the frequency of oscillation is given by

$$f = \frac{1}{2\pi\sqrt{C_o\,L_{eff}}}$$

for high Q, as compared to the unmodulated frequency

$$F = \frac{1}{2\pi\sqrt{C_o\,L}}$$

where C_o is oscillator tank capacity in farads

where L is oscillator tank inductance in henrys.

The injected inductance depends on the dynamic mutual conductance g_m in mhos which also depends upon the bias. The value of g_m will vary about the normal bias value as the modulating signal is applied to the reactance tube. Thus the induced value of the inductance will depend upon the value of the modulating voltage.

Consequently the reactance injected across the terminals of the oscillator tank is actually the sum of two reactances X $+\Delta$X sin ωt, where X depends only upon the bias of the tube and its operating characteristics while ΔX sin ωt depends upon the audio signal supplied across the reactance of the modulator tube.

It is this fixed value of reactance that depends only on the bias of the tube that will be used to correct for the slow frequency drift of the master oscillator. This bias is either automatically increased or decreased by means of the discriminator circuit to correct for the frequency drift.

A typical discriminator circuit known as Foster-Seeley circuit is shown in Figure 4.

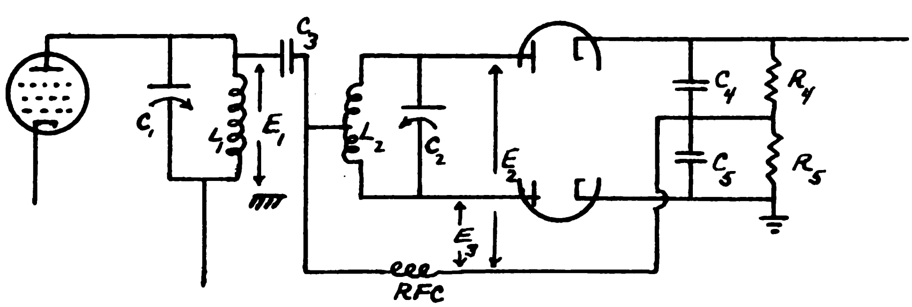

Figure 4. Discriminator Circuit

The two diode rectifiers work into equal high resistances R_4 and R_5 and the equal condensers C_4 and C_5 having low reactances at the carrier frequency while having high reactance at the highest audio frequency. The direct coupling condenser C_3 has negligible reactance at the carrier frequency. In general, loosely coupled resonance circuits, owing to the resonance current in the primary, will induce a voltage across the tuned secondary 90 degrees out of phase with the primary voltage.(3)

Thus for operation at the center frequency E_2 leads E_1 by 90 degrees. E_2 is 180 degrees out of phase with E_3 because of the center tapped secondary, or E_2 equals a minus E_3 and consequently E_3 lags E_1 by 90 degrees.

At the normal frequencies for frequency modulation intermediate frequency transformers, C_3 acts as a short circuit and has negligible reactance and thus the voltage E_1 is essentially applied across the RF choke and is E_1 in value.(4) Also at this relatively high frequency the condensers C_4 and C_5 charge up to the peak voltages $E_1 + E_2$ and $E_1 + E_3$ respectively and discharge only slightly because of the high resistances R_4 and R_5 before they recharge again.(5) Therefore, they remain charged at the peak value voltage. The upper diode will pass only the positive peaks of the voltage sum of $E_1 + E_2$, while the lower one will pass the negative peaks of the voltage sum of $E_1 + E_3$.

Assume that

$E_1 = E_m \sin \omega t$

$E_2 = E_m \sin(\omega t + \phi)$, where ϕ is the angle E_2 leads E_1 and depends upon the deviation.

$E_3 = E_m \sin(\omega t - \phi)$

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(3) Ibid. p.195.
(4) & (5) Ibid. p.201.

For $\phi = 90^\circ$ the voltage across the condensers is given by

$$E_4 = E_1 + E_2 = E_m\left[\sin \omega t + \sin(\omega t + 90^\circ)\right]$$
$$= E_m(\sin\omega t + \cos \omega t)$$
$$E_5 = E_1 + E_3 = E_m\left[\sin \omega t + \sin(\omega t - 90^\circ)\right]$$
$$= E_m(\sin \omega t - \cos\omega t)$$

But since E_4 is made of positive peaks while E_5 is made up of negative peaks, the condensers C_4 and C_5 are charged to a peak value of equal magnitude but of opposite polarity. The phase angles of the voltages E_4 and E_5 are of no importance as the condensers are considered to remain fully charged at their peak value. For a deviation such that $\phi = 45^\circ$

$$E_4 = E_1 + E_2 = E_m\left[\sin \omega t + \sin(\omega t + 45^\circ)\right]$$
$$= E_m\left[\sin \omega t + 0.707\ (\sin\omega t + \cos \omega t)\right]$$
$$= E_m(1.707 \sin \omega t + 0.707 \cos \omega t)$$
$$E_5 = E_1 + E_3 = E_m\left[\sin \omega t + \sin(\omega t - 135^\circ)\right]$$
$$= E_m\left[\sin \omega t - 0.707\ (\sin \omega t + \cos \omega t)\right]$$

Therefore the direct voltage output $= E_4 - E_5 = 1.4\ E_m$ $(\sin \omega t + \cos \omega t)$ where again the angle is of no value. Thus the two voltages across the condensers are additive and have a plus value. In a similar manner for $\phi = -45$ degrees, the output voltage will be negative.

Frequency stabilization by means of a frequency discriminator is obtained by the correction voltage being applied to the modulator grid and thus varying the mutual conductance of the tube.

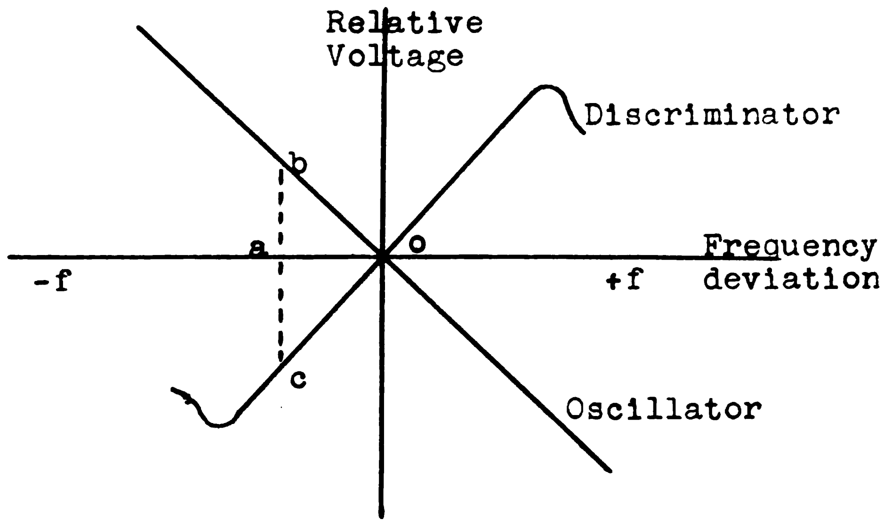

Figure 5.

A typical discriminator and modulator-oscillator characteristics have been drawn in Figure 5. Assume that the oscillator has drifted from its center frequency, o, to point a. A voltage ac is obtained from the discriminator and, if exactly equal to voltage ab, will bring the oscillator back to point o. If not and the voltage ac is greater than the voltage ab, then the oscillator will pass through point o to a point on the plus deviation frequency side by the difference in voltage. This, in turn, will be corrected to some extent by the plus discriminator voltage causing the actual deviation to approach nearer to point o. As each successive correction is only approximate, the master oscillator will tend to oscillate back and forth from plus to minus values of frequency deviation, but the master oscillator will finally come to rest at a frequency near its mean value.

Consequently, the stabilization depends to a great extent on the voltages of the output of the discriminator and voltage required for a given deviation of the oscillator, but to a much greater extent on the similarity between the two characteristics. If they are equal in slope and magnitude at any given point, it would be possible to have zero deviation and perfect correction.

CONSTRUCTION AND TESTS:

A transmitter consisting of a reactance tube modulator, electron coupled oscillator and feedback stabilizing circuit was built on a single chasis. The schematic diagram of the transmitter is on page 16, Figure 6.

A 6SJ7 pentode tube was chosen for the reactance tube modulator as it fulfills the requirements of high plate resistance, sharp cutoff and nearly linear mutual conductance characteristic. The mutual conductance of the tube was measured by means of the bridge circuit,(6) Figure 7.

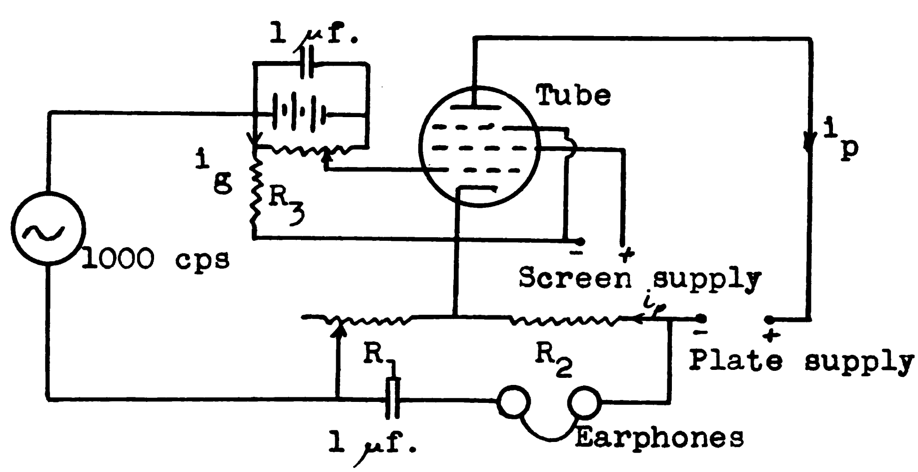

Figure 7. Measurement of g_m.

Two variable power supplies are used, one for the screen supply and the other for the plate supply. This was required because the screen voltage must be held

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(6) Terman, F. E.; Measurements in Radio Engineering; New York, McGraw-Hill Book Company, Inc., p.166; 1935.

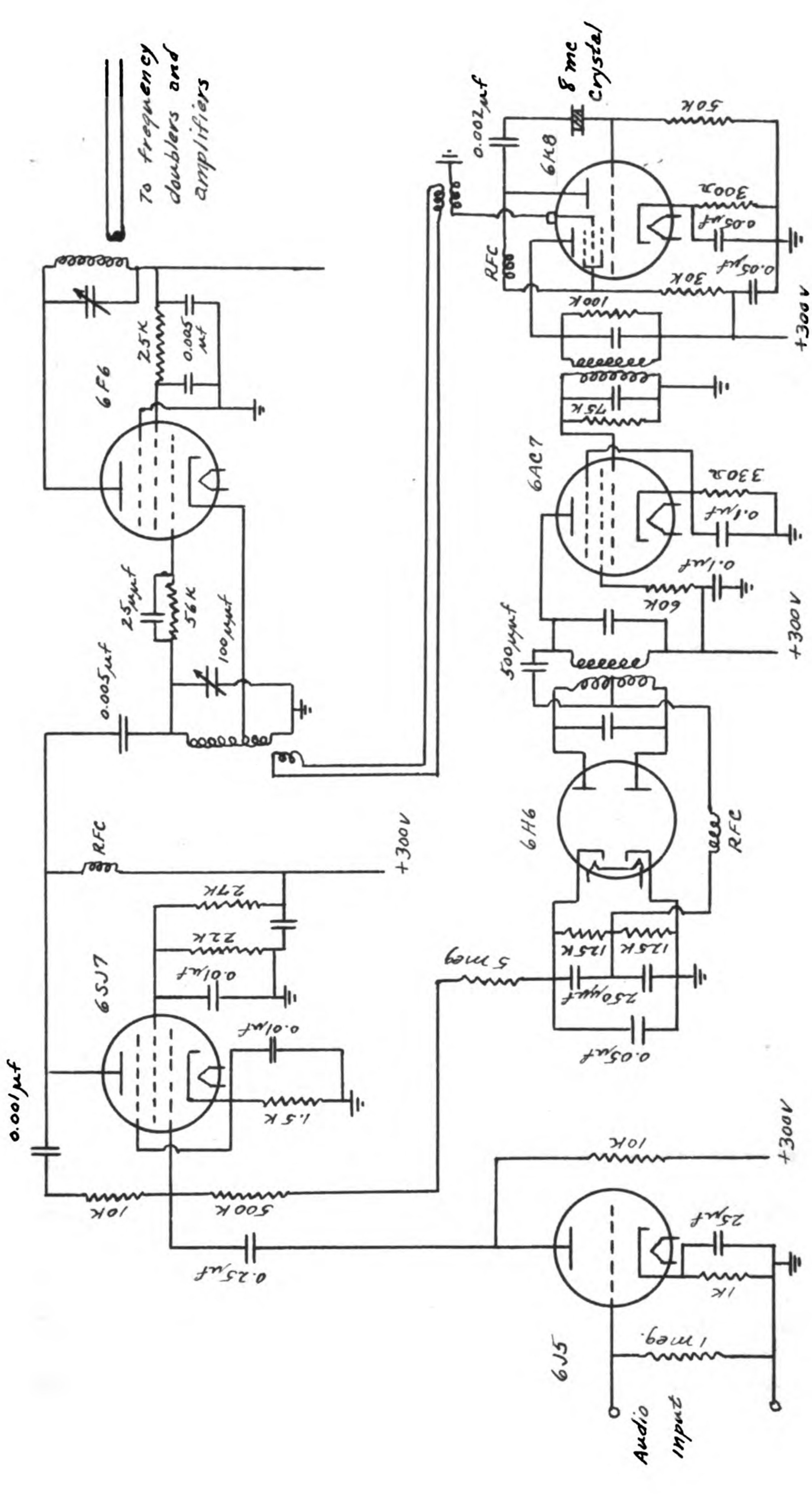


Figure 6. Schematic diagram of Experimental Transmitter

constant as the mutual conductance is critical with respect to fluctuation of the screen grid voltage and also the screen current must not flow through resistor R_2. The value of the mutual conductance for a given bias is given by the ratio R_1/R_2R_3 which may be proved in the following manner:

$e_g = i_g R_3$ where e_g is the signal voltage applied to the grid.

For no sound in the earphones,

$i_g R_1 = i_p R_2$ as i_g also flows through R_1 for the oscillator voltage is applied across the resistors R_1 and R_3 in series.

$$i_p = \frac{i_g R_1}{R_2}$$

But

$$g_m = \frac{i_p}{e_g} \qquad E_b = K$$

$$g_m = \frac{i_g R_1}{R_2 e_g} = \frac{i_g R_1}{i_g R_2 R_3} = \frac{R_1}{R_2 R_3}$$

The mutual conductance characteristic of the 6SJ7 tube for screen grid voltage of 125 volts and plate voltage of 300 volts is shown in Figure 8, page 18.

The reactance tube modulator was designed so as to use the grid to cathode capacitance of the tube for the reactance C, Figure 3, page 6. There are several

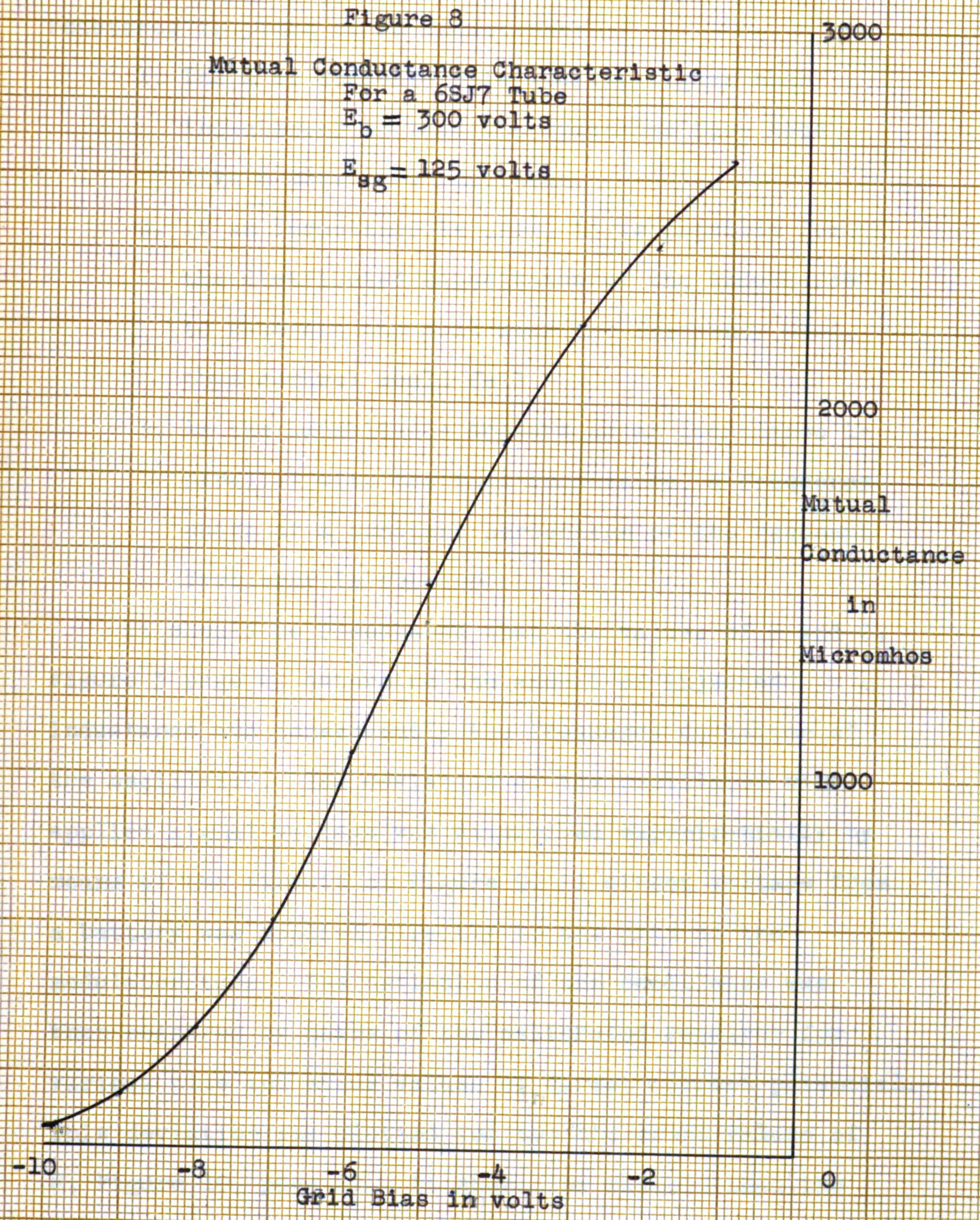


Figure 8
Mutual Conductance Characteristic
For a 6SJ7 Tube
E_b = 300 volts
E_{sg} = 125 volts
3000
2000
1000
0
Mutual
Conductance
in
Micromhos
-10
-8
-6
-4
-2
Grid Bias in volts

advantages in using a condenser to produce the injected reactance in place of an inductance:

1. The Q of condensers is usually higher than inductances so that the reactance tube acts like a more pure reactance.
2. If an inductance is used, it is possible for the distributed capacitance of the inductance to resonant the coil near the frequency used, thus control would fail.
3. As the capacitance appears as an inductance in parallel with the tank inductance, a frequency shift of a constant percentage of the resonant frequency is obtained.

It should be remembered that the values of R and C, Figure 3 page 6, determine the amount of injected inductance and consequently the frequency deviation of the oscillator. The deviation of the oscillator with applied signal voltage was determined experimentally by means of the circuit of Figure 9. A direct voltage from a battery was applied directly to the grid of the modulator tube. The deviation of the oscillator was then measured by means of the calibrated receiver for various plus and minus values of direct current potential. This deviation was plotted for two different values of R, Figure 10, page 21. It should be noticed that the

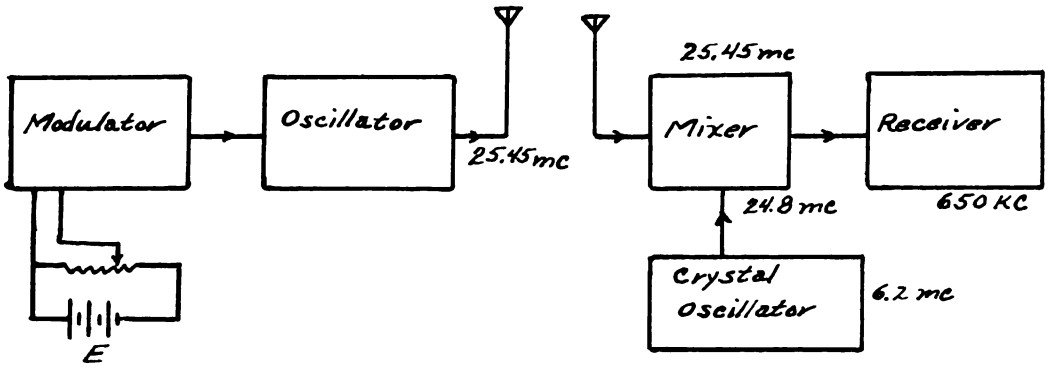


Figure 9.

deviation decreases with an increase in R. This is as it should be for the smaller the injected inductance in parallel with a fixed inductance, the greater the change in effective inductance of the oscillator tank.

The electron coupled oscillator was chosen because of its inherent frequency stability with voltage changes. The plate of the oscillator was tuned to the second harmonic of the grid oscillating frequency. A dial was placed on the shaft of the main tuning condenser of the oscillator and the frequency of oscillation was measured by means of an absorption type wave meter. To provide the calculated frequency of oscillation, the inductance and distributed capacity of the oscillator coil had to be determined. This was done with a Q-meter in the following manner:

The unknown oscillator coil was connected to the

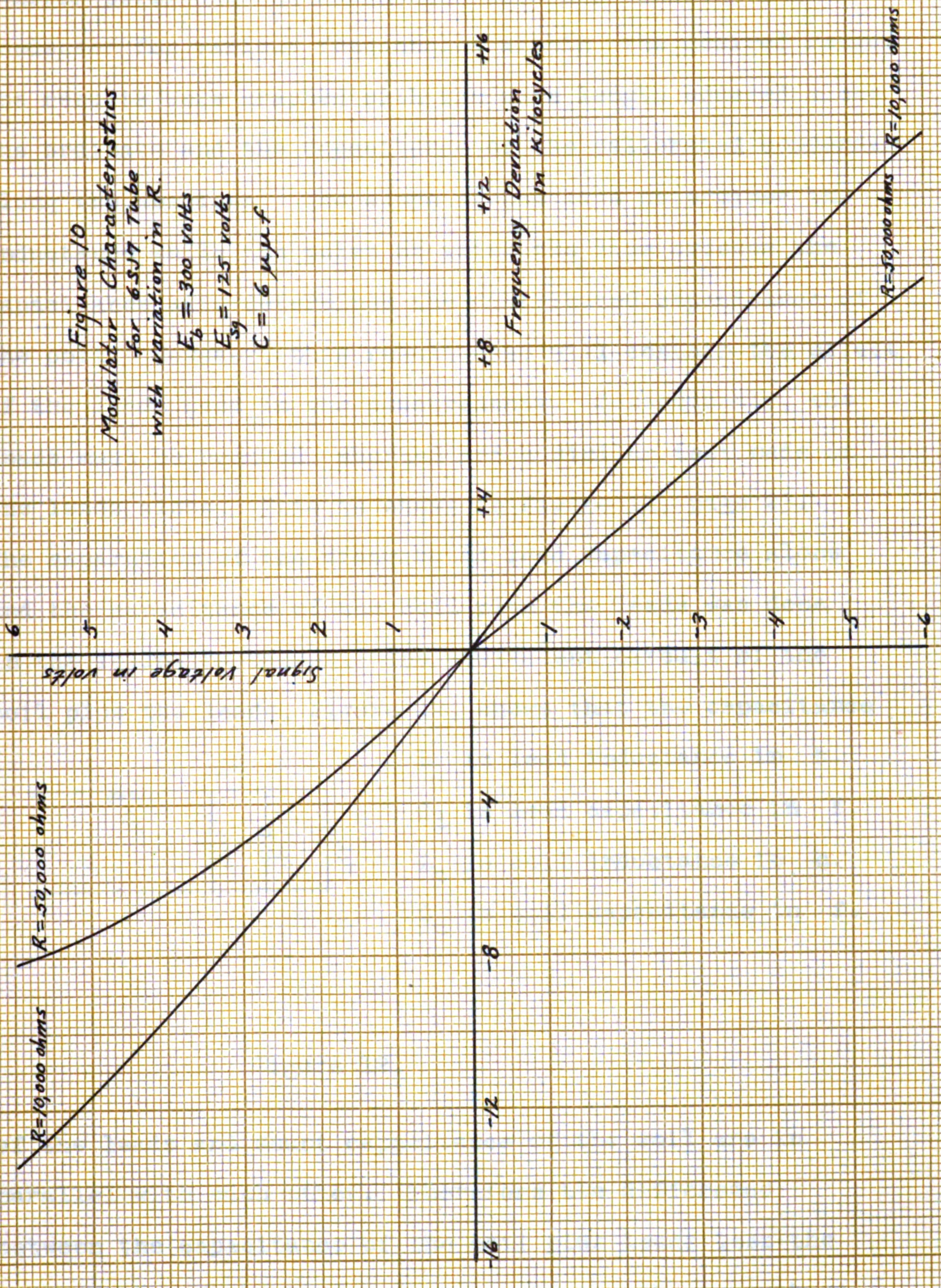
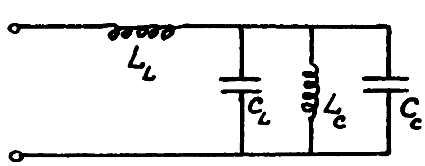


Figure 10
Modulator Characteristics
for 6SJ7 Tube
with variation in R.
E_b = 300 volts
E_{sg} = 125 volts
C = 6 μμf
Frequency Deviation
in Kilocycles
+16
+12
+8
+4
-4
-8
-12
-16
Signal Voltage in volts
6
5
4
3
2
1
-1
-2
-3
-4
-5
-6
R=10,000 ohms
R=50,000 ohms
R=50,000 ohms
R=10,000 ohms

Q-meter terminals and resonanted with a precision calibrated condenser for various frequencies within the desired range. The results were graphed with the wave length squared along the ordinate and the capacitance of the calibrated condenser along the abscissa. The slope of the line determines the inductance while the point at which the line crosses the capacitance axis determines the distributed capacitance of the coil. However, this result also will contain the effect of the leads used in the measurements. Consequently, the leads must be removed, shorted and a similar test made on the leads alone. This is shown in Figure 11, page 23. The separation of the distributed lead capacitance alone and the capacitance of the coil plus the leads was done in the following manner. The equivalent circuit of the coil plus the leads, Figure 12, shows that the capacitance



L_L is lead inductance in h.
C_L is lead capacitance in f.
L_c is coil inductance in h.
C_c is coil capacitance in f.

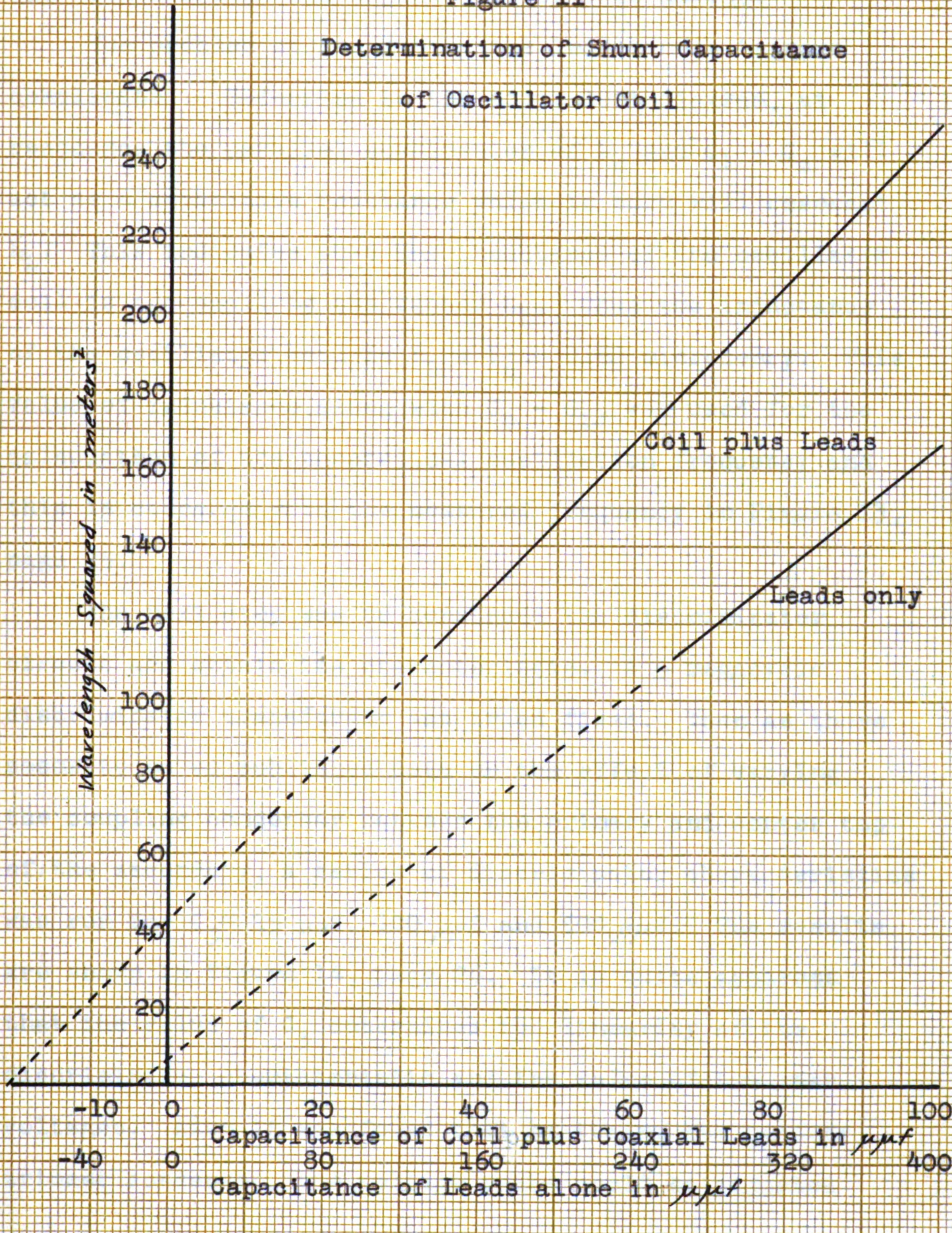
Figure 12.

of the leads and shunt capacitance of the coil are in parallel with each other. Therefore the difference between the capacitance of the coil plus leads less the capacitance of the leads alone results in the true shunt

Figure 11

Determination of Shunt Capacitance

of Oscillator Coil



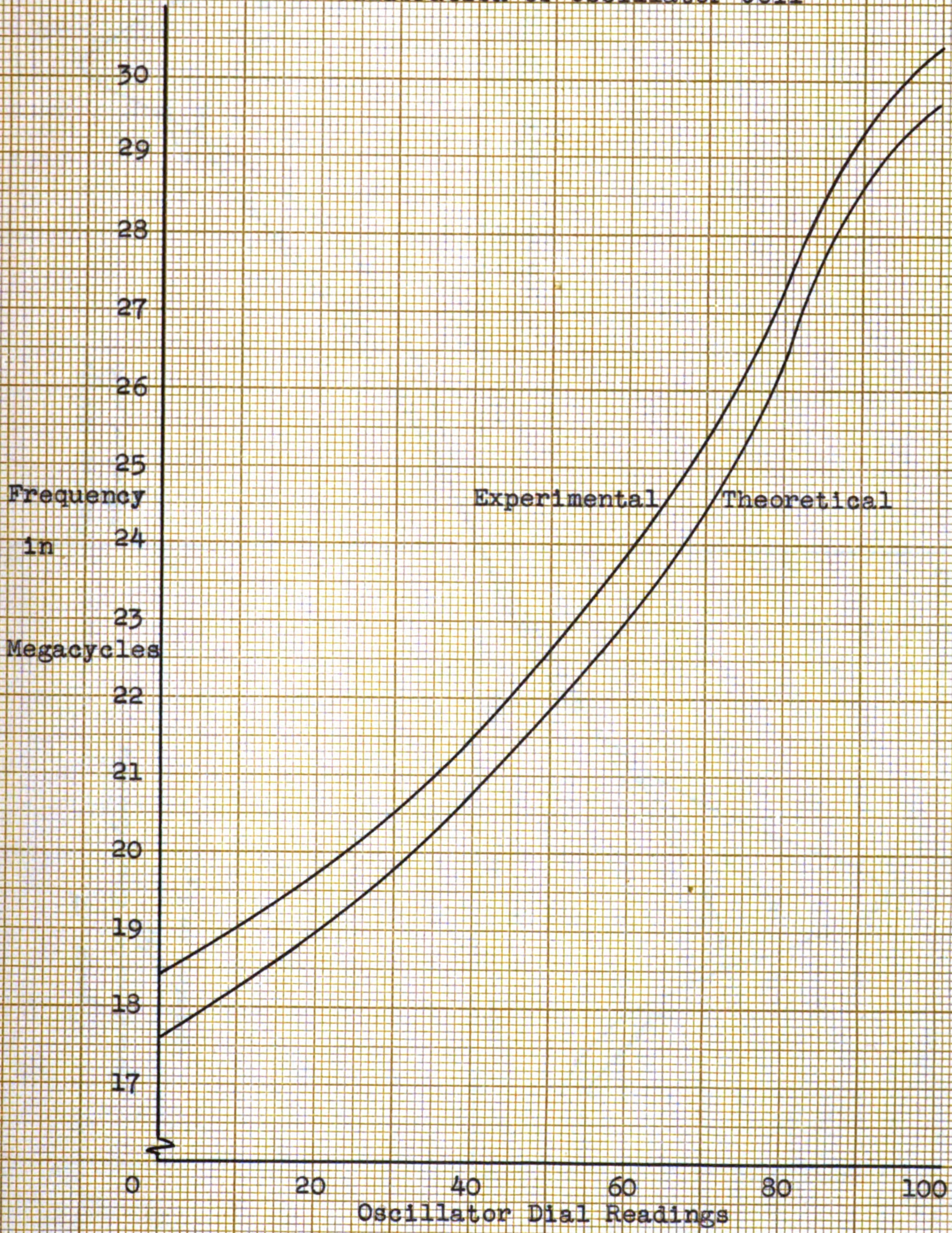
capacitance of the oscillator tank coil. This capacitance will also be in parallel with the main tuning condenser and will increase the capacitance by this amount.

The problem of separating the inductances is more complicated. Referring to the equivalent diagram, at resonance the parallel combination of L_c and $C_L - C_c$ will act as a capacitive reactance which in turn will resonant L_L. This indicates that the inductance of the oscillator coil is too small by the factor L_L. Thus the inductance of the oscillator coil is $L_L + L_c = 0.68$ microhenry. This value of inductance, along with $C_c - C_L$, was used for the calculation of the theoretical oscillation frequency and this is compared with the measured frequency in Figure 13, page 25.

The next step was to construct the discriminator circuit and obtain its characteristic. A 5 megacycle discriminator transformer was tried first. Then as there seems to be no published data on the effect of varying the coupling condenser between the primary and center tap of the secondary, a series of discriminator characteristics was run for $C_3 = 25\ \mu\mu f$, $100\ \mu\mu f$ and $500\ \mu\mu f$. The results are shown in Figure 14, page 26. It is quite apparent that the value of C_3 determines the linearity of the discriminator characteristic and the value of the peak voltages. Also it was found that by tuning the primary trimmer condenser, the voltage peaks could be adjusted

Figure 13

Calibration of Oscillator Coil



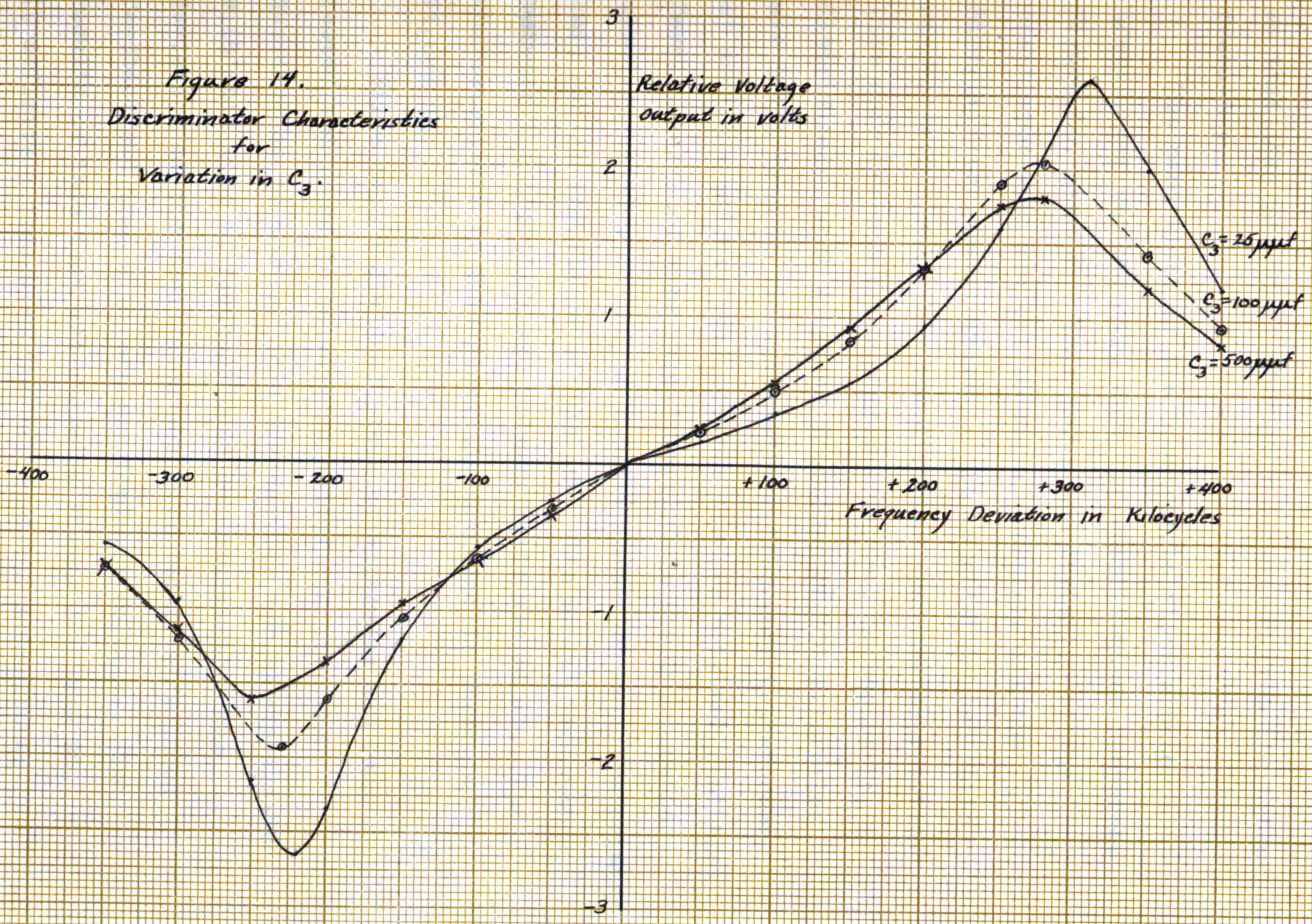


Figure 14.
Discriminator Characteristics
for
Variation in C_3.

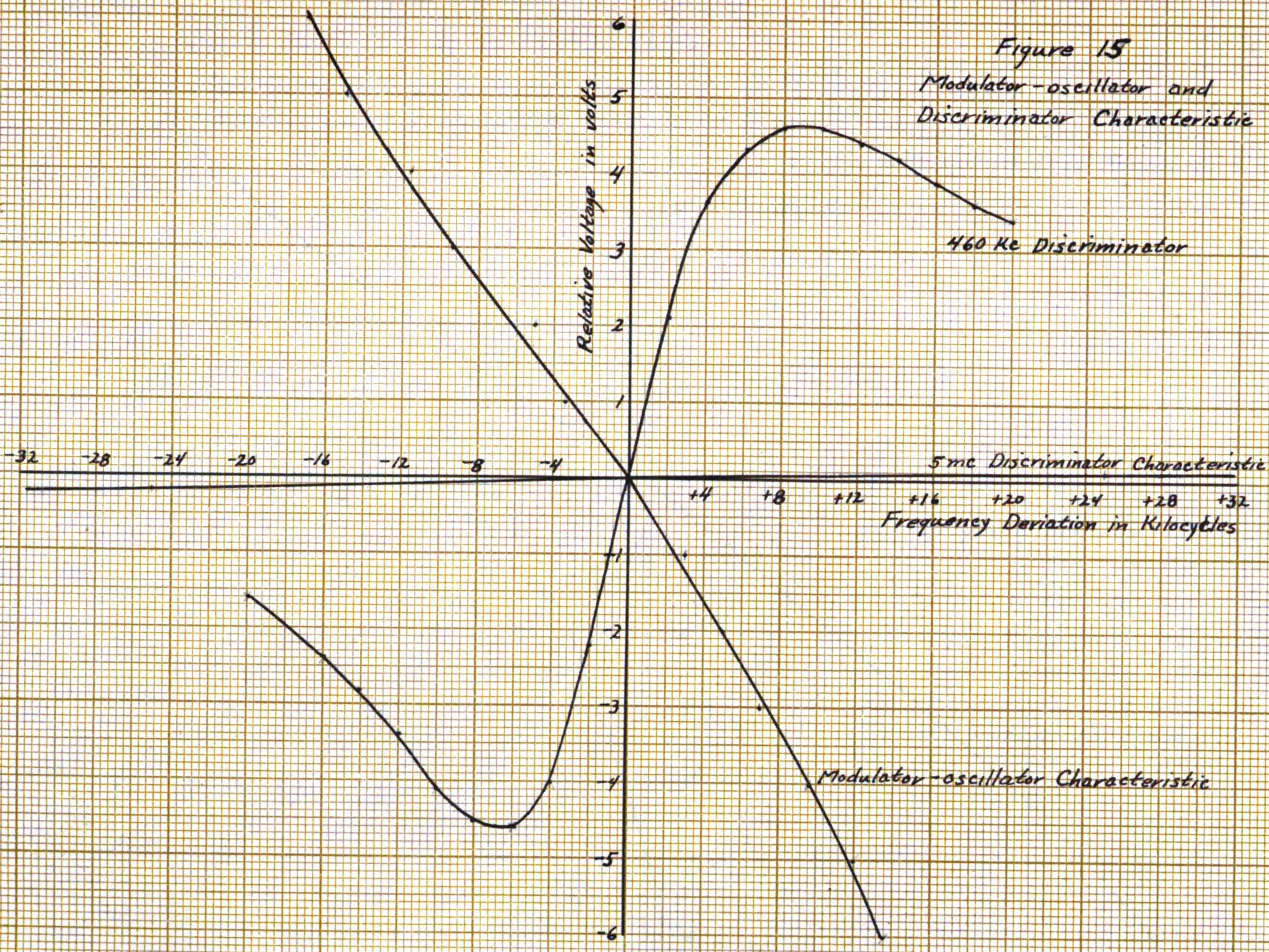
so that they had equal frequency deviation from the center frequency.

The band width of the 5 megacycle discriminator transformer was much too wide for stabilization purposes, Figure 15, page 28. This shows the deviation of the oscillator with respect to signal voltages and the discriminator characteristic. It is possible to obtain stabilization only when the discriminator characteristic lies near the modulator characteristic. Consequently, a discriminator with a center frequency of 650 kilocycles was built from an old intermediate frequency transformer by adding a primary coil between the two original windings. Several turns of wire were removed from the two outside windings until each had an inductance of 500 μh. The primary coil had an inductance of 1020 μh. The mutual inductance between the secondary and primary coils was 42 μh. The characteristic of this discriminator also is shown in Figure 15.

Since each individual piece of apparatus has been tested and found to be working satisfactorily, the question as to whether this transmitter can be stabilized with this type of feedback must be determined. The deviation of the oscillator was measured first without feedback and then with maximum feedback voltage. The results of this test are shown in Figure 16, page 29. It definitely indicates the value of the stabilizing

Figure 15

Modulator-oscillator and Discriminator Characteristic



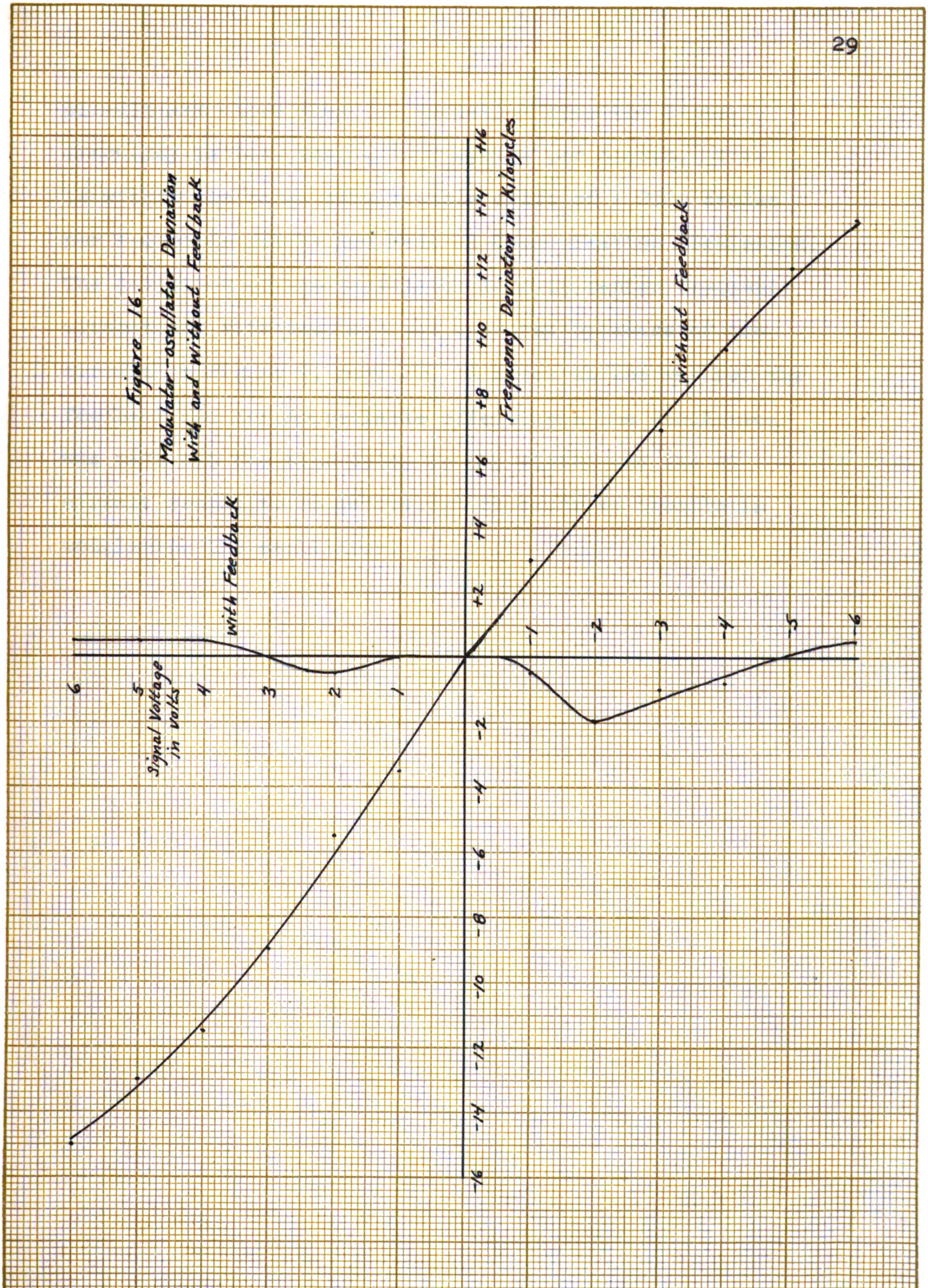


Figure 16.
Modulator-oscillator Deviation with and without Feedback

circuit and shows that the variation from the center frequency is less than ± 1000 cycles per second. This is within the range of allowable drift of ± 2000 cycles per second as set by the Federal Communication Commission. The deviation of the oscillator from it center frequency without and with feedback was measured by means of the circuit in Figure 9, page 20. A check to see whether the feedback had any appreciable effect upon the modulation was made but the time delay in the wiring and the RC circuit seemed to be sufficient to cause no trouble in modulating the oscillator.

CONCLUSIONS:

The frequency stability of the oscillator was very good with this type of stabilization circuit. However, this system of stabilization is not recommended except in portable transmitters as it has certain faults. The feedback circuit must be very stable with respect to voltage changes in order to prevent variations in output voltage of the discriminator other than that caused by frequency drift of the master oscillator. This can be prevented to some extent by the use of a limiter stage between the mixer and discriminator.

The variation in tube constants with age and from tube to tube of the same make and type will cause differences in the various characteristics of the discriminator and modulator-oscillator. When changing tubes in the modulator section, the different tube constants will mean different modulator-oscillator characteristic and, thus, correction characteristic. This can be eliminated to some extant by careful selection of replacement tubes.

This method has not found much practical application because of its instability. At the present time, the most commonly used system is that similar to the one used by the Western Electric Company which uses a motor to vary the main oscillator tuning condensers for correction.[7,8]

Another method which is finding much popularity and which is similar in principle to the frequency discriminator system is the use of a phase discriminator. The phase discriminator has an output characteristic much the same as the frequency discriminator but is proportional to the difference in phase existing between the crystal oscillator and transmitter frequencies. This latter method is reported to be much better than that of the tested system as it is a great deal more stable.[9]

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(7) Boykin, FM Frequency Control Systems, Radio, pp.20-22, 62-63, February 1946.

(8) Silver, Federal FM Broadcast Transmitter, FM and Television, pp.34-35, February 1946.

(9) Marchand, Direct FM Frequency Control Methods, Communications, pp.30-35, July 1946.

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