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INVESTIGATION OF METHODS AND TECHNIQUES FOR DETECTING UNWANTED CRYSTAL MODES

THIRD QUARTERLY REPORT

December 1, 1956 to March 1, 1957

SIGNAL CORPS CONTRACT NO. DA-36-039 SC-72378

DEPARTMENT OF THE ARMY PROJECT NUMBER 3-24-02-072

SIGNAL CORPS PROJECT NUMBER 867B

PLACED BY

UNITED STATES ARMY SIGNAL CORPS
ENGINEERING LABORATORIES
FORT MONMOUTH, NEW JERSEY

[redacted]

MOTOROLA, INC.
CHICAGO, ILL.

INVESTIGATION OF METHODS AND TECHNIQUES FOR DETECTING UNWANTED CRYSTAL MODES

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The object of this investigation is to develop a crystal oscillator type of test set for the purpose of detecting unwanted crystal modes in the frequency range of 1 to 100 Mc.

SIGNAL CORPS CONTRACT NO. DA-36-039 SC-72378
SQUIER SIGNAL LABORATORY TECHNICAL REQUIREMENTS
FOR
PR&C 56-ELS/D-3608, DATED FEBRUARY 13, 1956

DEPT. OF THE ARMY PROJECT NUMBER 3-24-02-072
SIGNAL CORPS PROJECT NUMBER 867B

MOTOROLA, INC.

B. NIEDERMAN
J. LOOS

Purpose

The basic purpose of this study is to develop one or more crystal oscillators, covering the range of 1 to 100 Mc, which are more susceptible to operating on a spurious mode than any other oscillator in that particular frequency range.

Crystal manufacturers have, for some time, employed an elaborate setup to plot the main and spurious modes of a crystal directly on graph paper. Spurious responses whose series resistances are four times that of the main mode escape detection entirely, showing the extreme inadequacy of this system.

This places a double burden upon the military when crystals are to be purchased. The first problem arises when spurious limits are to be specified for a crystal which must be suitable for a number of circuits. The second problem lies in the limitations of the detecting equipment itself. Both of these problems must be solved before the military procurement agencies are able to stockpile quantities of crystals for use in a variety of circuits.

An oscillator which is more capable of oscillating on spurious responses than any other known oscillator is the obvious solution to these problems. This oscillator, or series of oscillators, is to be incorporated into a military type of test set.

Abstract

The Butler and Hartley oscillator circuits are analysed to determine the highest values of crystal spurious resistances capable of sustaining oscillations.

The schematic diagrams of the 6-7 Mc. Butler and Hartley oscillator circuits, which have been developed, are given. Utilizing the derived equations, the highest values of spurious resistances capable of controlling oscillations in these two circuits are computed.

The main and spurious mode resistances and frequencies of the crystals used to test the oscillators are tabulated. The spurious responses detected by the test oscillators are indicated. The overall ability of the Hartley oscillator to detect spurious responses is given by a curve of highest spurious resistances detected vs. percent frequency difference from the main response. A similar curve, expanded to include only those responses within one percent of the main response frequency, is also obtained by the use of the similated spurious technique.

Publications, Lectures, Reports and Conferences

There were no publications, lectures, or reports during this quarter.

Mr. B. Niederman and Mr. J. Loos of Motorola conferred with Dr. Guttwein, Mr. O. Laydan, Mr. G. Gougoulis, and Mr. D. Pochmerski of S.C.E.L. at Fort Monmouth, N.J. on 17 December, 1956. Progress of the work up to date was discussed. The objectives of the contract were clarified and plans for the immediate future were discussed.

Factual Data

In the previous report it was concluded that an oscillator capable of detecting (i.e. - having its frequency of oscillation controlled by) crystal spurious responses must meet two main requirements. The first is high gain to compensate for the attenuation caused by a high resistance spurious mode in a series feedback path. The second requirement is that of extreme selectivity (i.e. - narrow bandwidth) to discriminate against a low main mode series resistance while permitting oscillations to be controlled by an adjacent high resistance spurious mode.

The Butler and the Series Mode Hartley oscillators were chosen as the most logical circuits because of their ability to meet the above two requirements and the added advantage of simplicity. Since the final equipment is to be used by inexperienced personnel, it must remain simple.

I. OSCILLATOR ANALYSIS

The conditions required for oscillations in terms of circuit parameters for the Hartley and Butler circuits are derived in the following sections. The resulting expression in each case is solved for the crystal series resistance (R), which when evaluated, becomes the highest value allowable for sustained oscillations.

In some cases it might be desirable to limit the value of this resistance. Therefore, in the Hartley circuit, the expression governing oscillations has been solved for "a" which is the inverse of the autotransformer turns ratio. In this manner the feedback may be adjusted to control the limiting value of detectable resistance.

A. Hartley Series Mode Oscillator

The Hartley oscillator schematic and its equivalent circuit are shown in Figs. 7a and 7b respectively.

We define Z_1 and Z_2 as

Eq. 1
$$Z_1 = \frac{R_g Z}{R_g + Z}$$

Eq. 2
$$Z_2 = \frac{R_k (R + a^2 Z_1)}{R_k + R + a^2 Z_1}$$

From Equation 1 and Fig. 7b:

Eq. 3
$$\frac{E_1}{E_k} = \frac{a Z_1}{R + a^2 Z_1}$$

From Equation 2 and Fig. 7b:

Eq. 4
$$\frac{E_k}{E_1} = \frac{u Z_2}{R_p + (1 + u) Z_2}$$

Multiplying Equation 3 by Equation 4 results in

Eq. 5
$$\frac{a u Z_1 Z_2}{(R + a^2 Z_1)(R_p + ((1 + u)) Z_2)} = 1$$

The term $(1 + u)$ may be simplified to (u) since it is intended to use a pentode or a high u triode in the Hartley circuit, therefore:

Eq. 5a
$$\frac{a u Z_1 Z_2}{(R + a^2 Z_1)(R_p + u Z_2)} = 1$$

In order to solve for R the equation for Z_2 must be reinserted since Z_2 is a function of R.

Eq. 5b
$$\frac{a u Z_1 R_k (R + a^2 Z_1)}{R_k + R + a^2 Z_1} = (R + a^2 Z_1)\left(R_p + \frac{u R_k (R + a^2 Z_1)}{R_k + R + a^2 Z_1}\right)$$

Solving for R and simplifying yields

Eq. 6
$$R = \frac{g_m a Z_1 R_k (1-a) - (R_k + a^2 Z_1)}{1 + g_m R_k}$$

To limit the value of detectable R, the turns ratio (a) of the coil is adjusted accordingly. Solving Equation 6 for "a" yields:

Eq. 7
$$a = \frac{g_m R_k Z_1 \pm \sqrt{(g_m R_k Z_1)^2 - 4 Z_1 (1 + g_m R_k)(R((1 + g_m R_k)) + R_k)}}{2 Z_1 (1 + g_m R_k)}$$

If the quantity under the radical is a positive value, there will be two solutions, either of which will satisfy the requirement. Any value of "a" between these two solutions will result in a higher detectable "R". If the quantity under the radical is made equal to zero, only one point on the coil may be tapped. If the quantity under the radical is negative, the circuit will require a lower value of R to produce oscillations.

B. Butler Oscillator

A generalized Butler oscillator schematic and its equivalent circuit are given in Figs. 8a and 8b respectively. The additional equivalent circuits of Figs. 8c and 8d are simplified versions of

Fig. 8h. In Fig. 8c the voltage generator of Fig. 8b ($u''E_2$) is replaced by a negative resistance equal to $-u''(R_p'' + Z_1)/(u'' + 1)$.

From Fig. 8 (note) equation 8 is obtained.

Eq. 8 $$Z_1 = \frac{ZR_g}{Z + R_g}$$

The quantities Z_2, Z_3 and Z_4 are defined as

Eq. 9 $$Z_2 = \frac{R_p'' + Z_1}{u'' + 1}$$

Eq. 10 $$Z_3 = \frac{R_k''Z_2}{R_k'' + Z_2}$$

Eq. 11 $$Z_4 = \frac{R_k'\ (R + Z_3)}{R_k' + R + Z_3}$$

From Fig. 8c Equation 12 is obtained.

Eq. 12 $$\frac{E_1}{E_2} = \frac{Z_1}{Z_2}$$

From Fig. 8d Equations 13 and 14 are obtained.

Eq. 13 $$\frac{E_2}{E_k} = \frac{Z_3}{R + Z_3}$$

Eq. 14 $$\frac{E_k}{E_1} = \frac{u'Z_4}{R_p' + (1 + u')Z_4}$$

Multiplying Equations 12, 13 and 14 yields

Eq. 15 $$\frac{u'Z_1Z_3Z_4}{Z_2(R + Z_3)(R_p' + (1 + u')Z_4)} = 1$$

Simplifying Equation 15 and substituting the value of Z_4 from Equation 11 yields

Eq. 16 $$\frac{u'Z_1Z_3}{Z_2} = (1 + u')(R + Z_3) + \frac{R_p'}{R_k'}(R + R_k' + Z_3)$$

Solving Equation 16 for R gives

Eq. 17 $$R = \frac{\frac{u'Z_1Z_3}{Z_2} - Z_3\left(1 + u' + \frac{R_p}{R_k'}\right) - R_p'}{1 + u' + \frac{R_p'}{R_k'}}$$

Simplifying results in

Eq. 18 $$R = \frac{R_k'}{Z_2}\ \frac{u'Z_1Z_3 - R_p'Z_2}{(1 + u')R_k' + R_p'} - Z_3$$

If the value of detectable R is to be limited, it is possible to do so by adjusting the gain of V'. This may be accomplished by adjusting the value of R_k'. Equation 18 may be solved for R_k' yielding:

Eq. 19

$$R_k' = \frac{Z_2 R_p'(R + Z_3)}{u'Z_1 Z_3 - R_p' Z_2 - Z_2(1 + u')(R + Z_3)}$$

By substituting the desired limiting value of R, the required value of R_k' is obtained.

II DEVELOPED OSCILLATORS

The oscillators described in this section were developed from preliminary circuits described in the second quarterly report. The Butler oscillator of Fig. 1 was originally described in Fig. 4 of the second quarterly report. (1) The Hartley series mode crystal oscillator of Fig. 2 was originally described in Fig. 1 of the previous report. The symmetrical oscillator of Fig. 3 was evolved from that of Fig. 1 in this report.

A. Butler Oscillator

The Butler crystal oscillator described in Fig. 4 of the previous report was constructed. The plate tank coil L_1 was constructed as a fixed coil rather than a tunable one since a higher "Q" was made possible by the substantial increase in diameter. The coil that was originally tried was about 13 microhenries. The tuning capacitor, which was connected from pin 6 to ground to facilitate mounting, was made a 7 to 47 uuf air variable. The tank circuit impedance was approximately 160,000 ohms since the "Q" of L_1 was about 300. However, this tank circuit was shunted by the plate resistance of the grounded-grid amplifier, about 5000 ohms. This results in a loaded "Q" of approximately 10. This was definitely not the selectivity desired but was utilized to determine the effect of a very high gain.

This circuit was tested and found to be highly unstable. At this point it was decided to decrease the gain of the grounded-grid amplifier stage and simultaneously improve the selectivity. A decoupling network was placed between the tank circuit and B+ and the plate tank impedance was lowered. These two changes are shown in Fig. 1. The resulting 4 uh coil, L_1, has a "Q" of about 250 resulting in a tank impedance of approximately 40,000 ohms. However, as used in the circuit, the loaded "Q" becomes about 27. The variable capacitor, C_7, is a ceramic trimmer which is used to set the range covered by the air variable C_6. The range covered by C_6 is slightly greater than 10% of the center frequency.

After wiring a capacitor in series with the crystal, resistances were substituted for the crystal to determine the maximum value at which oscillations would occur. This was determined to be over 1000 ohms. With this sensitivity it was possible to pick up and detect a large number of spurious responses. However, to further improve the selectivity of this circuit some of this sensitivity must be sacrificed. It was therefore decided to begin investigating the Hartley Series Mode Oscillator since the high "Q" desired would, in that particular circuit, be much more realizable.

The circuits appearing between the cathodes of V_1 in Fig. 1, which lead to the "Crystal Current" and "R.F. Indicator" terminals, were installed in this circuit for purposes of power measurements and oscillation indications. The network consisting of C_4, R_7, D_2 and C_{12} is the R.F. probe developed in the first quarter and is used to measure the R.F. voltage at the cathode of the grounded-grid

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(1) In Fig. 4 of the Second Quarterly Report, the lead from pin 6 to the 150 V terminal should be broken since it shorts out the tank circuit of L_1 and C_2.

In Fig. 5 of the Second Quarterly Report, the lead connecting C_3 to pin 2 should be broken. The disconnected end of C_3 should be grounded.

amplifier stage. The capacitors C_1 and C_3, due to the rectifying action of the diode D_1, charge up sufficiently to deliver a DC voltage across D_1 equal to the peak value of voltage across the crystal. The resistors R_4 and R_6 are used primarily for isolation of the metering instruments. It was experimentally determined that no additional losses occured by grounding R6 in order to obtain a ground reference for metering purposes.

B. Hartley Series Mode Oscillator

The original Hartley oscillator circuit, described in Fig. 1 of the second Quarterly report, was taken almost entirely from an oscillator presently being used as a second mixer oscillator in a commercial Motorola receiver. The original schematic had been modified to the extent of changing the tube type, adding a screen voltage adjustment and making the feedback circuit an inductive rather than a capacitive transformer.

In the ensuing tests it was determined that the inductances L_3 and L_4 were not necessary for our purpose. The inductance L_4 had been originally intended for a high impedance cathode load to attain a near unity gain from the cathode follower. The inductance L_3 had been used in conjunction with a series tuning capacitor for purposes of frequency adjustment. These two inductances were therefore discarded and a 470 ohm cathode load resistance placed in the circuit.

At this time the problem of L_2 was brought up. This is the inductance shunting the crystal which is used to tune out the shunt capacitance of the crystal. An inductance to shunt the crystal for this purpose is a logical idea when a narrow range of frequencies is to be covered by the oscillator. However, it would require an elaborate switch to select a proper inductance at any frequency between 1 and 100 Mc. At this frequency however, it is not even necessary to include L_2 in the circuit since the reactance of the crystal shunt capacitance is over 4000 ohms. The problem of minimizing the feed-through caused by the shunt capacitance of the crystal was postponed to the time when higher frequency oscillators would be considered since this capacitive effect would be much more detrimental at that time.

It soon became apparent that, although the "Q" of L_1 was about 300, shunting this tank circuit with a grid resistor of only 10,000 ohms lowered the "Q" to about 17. The grid resistor was therefore increased to 1 megohm. The loaded "Q" of the tank circuit then became 256. This circuit however, proved very unstable and would oscillate even with the crystal out of its socket. At this point it was decided that the impedance of the tank circuit was much too high and should be lowered. The resultant circuit is now shown in Fig. 2 of this report.

The Hartley oscillator circuit of Fig. 2 was used to obtain the "Spurious Detection Sensitivity" curves of Fig. 5 and Fig. 6. The metering networks leading to the "R.F. Indicator" and "Crystal Current" terminals are identical to those described for Fig. 1. The crystal current indication in this circuit, however, was obtained by metering the voltage across a 100 ohm resistor in series with the crystal. The capacitor, C_5, was wired into the circuit to prevent DC loading of the cathode when resistances were substituted for the crystal.

In order to determine the most efficient point at which to tap the coil, L_1, it was decided to try each turn while recording the output voltage obtained with a crystal controlling the oscillation.

The maximum value of resistance which would sustain oscillations for each tap point was also recorded. The results are shown in Table I.

TABLE I

SELECTION OF MOST EFFICIENT FEEDBACK RATIO

Turns from ground at which tapped	R.F. output at Cathode with crystal used	Max. Resistance sustaining oscillations
9		
8	1.14 Volts	
7	1.5	
6	2.15	680 ohms
5	2.6	1800 "
4	2.8	2200 "
3	3.0	2200 "
2	2.98	1500 "
1	2.15	150 "

Based on this information the tap was placed on the fourth turn from ground. (The coil, L_1, had a total of 10.5 turns.)

At this point it is possible, by the use of equation 6, to compare the theoretical and experimental value of maximum R for which oscillations will continue. In order to do so the following parameters have been utilized. For a 6AK5 vacuum tube with a plate voltage of 150 and a screen voltage of 120, the transconductance (g_m) is given as approximately 5000. With L_1 having a total of 10.5 turns and the tap being placed on the fourth turn, "a" becomes .381 and a^2 equals .145. The inductance, L_1, as measured on the "Q" meter, is 3.78 uh. Its "Q" was measured as 250. This makes Z, the equivalent impedance of the tank circuit at resonance, equal to 38,500 ohms. With a grid resistor, R_g, of 1 megohm the value of Z_1 (equation 1) becomes 37,200 ohms. The value of R_k as given in Fig. 2 is 470 ohms.

Substituting these values into equation 6 results in 4.39 K ohms as being the largest value of R which is theoretically detectable in the oscillator circuit of Fig. 2. This value is quite different from the maximum value of 2.2 K ohms which was determined in Table I. However, when the vacuum tube which had been used in obtaining the data for Table I was tested in a transconductance type tube tester under the actual operating voltages, the g_m was measured as 3500 umhos instead of the 5000 which had been obtained from published data. Using this value of transconductance the maximum value of R was once again calculated and this time came out as 3.23 K ohms.

The difference existing between the calculated and the experimental value of maximum R is probably due to a number of assumptions and additional factors which were not taken into account. For example, the transformer action of L_1 was assumed to be 100% efficient. The coil itself was fairly large in diameter with the turns fairly well spaced to maintain the good "Q". Undoubtedly this led to inefficiencies which were not taken into account in the calculations. The load offered by the metering circuits as well as the shunt capacitances between the cathode and ground were entirely disregarded in making the calculations.

For most applications it is possible to use equation 6 to obtain the maximum value of R as a first approximation. The actual limiting value of R would in any case be determined by experimentation.

A simple method of controlling the limiting value of R is by tapping the coil at a point yielding less over-all feedback. Instead of fixing the value of "a" and determining the limiting value of R with equation 6, it may prove desirable to set the limiting value of R and determine the value of "a" necessary to set this limit. For example, by using the previously determined values for g_m, R_k, Z_1 and the desired limiting value of R (let us arbitrarily use 2000 ohms), the solution of equation 7 gives two values for "a". These are .116 and .504.

C. Symmetrical Butler Oscillator

The schematic of a symmetrical Butler oscillator appears in Fig. 3. This circuit was evolved from the Butler circuit appearing in Fig. 1. The advantages of the Butler oscillator circuit of Fig. 3 over that in Fig. 1 are - greater simplicity - higher stability - more versatility. The circuit was originally designed and constructed around a 12AT7 vacuum tube. The circuit is, however, equally useable with either a 12AU7 or a 12AT7 vacuum tube. The data given in the following section (III) indicates their relative ability to detect sp spurious responses. The impedance level of the plate tank circuit is the same as that of Fig. 1 with the padder condenser, C_{12}, and the trimmer condenser, C_{11}, setting the center frequency while the air variable, C_{10}, is used to tune a 10% frequency range.

Using the circuit values of Fig. 3 it is possible to calculate the value of limiting R as in the case of the Hartley oscillator. The following constants are used in the calculations: R_g = 560,000 ohms, Z = 38,500 ohms, $u' = u'' = 18$, $R_p' = R_p''$ = 7000 ohms, $R_k' = R_k''$ = 270 ohms. Substituting the values for Z and R_g into equation 8 yields the value for Z_1 = 36,100 ohms. Substituting the values of R_p'', Z_1 and u" into aquation 9 yields Z_2 = 2,270 ohms. Substituting the values for R_k'' and Z_2 into equation 10 gives Z_3 = 259. Substituting these values into equation 18 gives a value of R = 1,210 ohms.

Resistances were substituted for the crystal to determine the actual highest value of R permitting oscillations. This maximum value is 1100 ohms. A 1200 ohm resistor was too high and would not cause oscillations to occur.

III SPURIOUS DETECTION DATA

In the Second Quarterly Report it was stated that, of the 1000 crystals tested for spurious responses, 352 of them were useable. The basis for this statement was that the rejected crystals had no spurious responses less than 100 ohms. However, as soon as the oscillator testing began it became apparent that this limit should have been raised to well above 1000 ohms. The 352 crystals which were acceptable had at least 1 spurious of less than 100 ohms series resistance. Of this latter group, 100 were selected for testing the Hartley oscillator and two versions of the Symmetrical Butler oscillator. The high "Q" version of the Butler oscillator uses a 12AT7 vacuum tube and the low "Q" version uses a 12AU7 vacuum tube. The results of these tests are shown in Table II.

In Table II the spurious were numbered according to their separation from the main response. The last three columns of this table indicate the ability of the particular oscillator to detect the various spurious responses. An X mark appearing on the line of a spurious indicates that the oscillator, in whose column the X appears, was able to oscillate under the control of that spurious.

The spurious data of Table II is obtained in the following manner. A crystal is inserted into the socket and the plate tank tuned to obtain an output voltage. The tank circuit is then tuned lower in frequency until there is no longer any output. The resonant frequency of the tank circuit is then raised until an output is indicated. This output is then monitored by obtaining a beat note at the output of a hetrodyne frequency meter. As the tank circuit is tuned higher in frequency this beat note varies but, by varying the tuning of the frequency meter, is maintained in the audible range. As the tank circuit is tuned higher the audible beat note will suddenly disappear. If, at this time, a DC voltage is still present at the R.F. Indicator terminal it means that the oscillator is being controlled by a spurious response. The hetrodyne frequency meter is then tuned higher in frequency until the audible note is once again heard in the vicinity of the spurious response controlling the oscillations.

This procedure is repeated at this spurious response until the audible note is once again lost and regained by retuning the hetrodyne frequency meter to the controlling spurious. The frequency of each of these spurious is noted. The difference in frequency between the spurious and the main response is calculated as a percent of the main response frequency and noted in Table II. The resistance of the spurious that were detected, as well as the ones which were not detected, were obtained by the series resistance method as reported in the previous quarterly report.

During the tuning operations of the tank circuit it is advantageous to intermittently turn off the B+ voltage and immediately turn it back on again. This minimizes the pulling effect of the mode that is controlling the oscillations. It is possible for the controlling mode to hold the frequency as the tuned circuit skips an adjacent response and arrives at still another response at which the circuit will oscillate when the controlling response loses control. By interrupting the B+ voltage the oscillator is more likely to detect the spurious between these two. In some cases it is possible by reverse tuning to

detect a spurious that was passed over when tuning from a lower to a higher frequency. It is also possible by careful tuning to maintain oscillations on two frequencies simultaneously.

A. Data

TABLE II

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator Hartley	Butler 12AT7	12AU7
201	----------	----------	7	----------	----------	----------
	1	.63	1300			
	2	1.09	185	X	X	
	3	1.17	1550			
	4	1.47	91	X	X	X
	5	3.36	3650			
	6	5.62	2400			
202	----------	----------	10	----------	----------	----------
	1	.47	2650			
	2	.72	81	X	X	X
	3	.99	2000			
	4	1.34	2400			
	5	2.67	1750	X		
203	----------	----------	14	----------	----------	----------
	1	.68	89	X	X	X
	2	1.26	320			
	3	1.28	160	X	X	X
	4	1.37	1300			
	5	3.04	3650			
204	----------	----------	7	----------	----------	----------
	1	.82	145	X	X	
	2	1.33	62	X	X	X
	3	1.70	87	X	X	X
	4	3.62	3650			
205	----------	----------	7	----------	----------	----------
	1	.63	530			
	2	.82	770			
	3	1.32	89	X	X	X
	4	1.44	2300			
	5	1.74	85	X	X	X
206	----------	----------	6	----------	----------	----------
	1	.67	425			
	2	.89	210	X	X	

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator		
					Butler	
				Hartley	12AT7	12AU7
	3	1.49	64	X	X	X
	4	1.96	70	X	X	X
	5	3.38	920	X		
	6	3.66	240	X	X	X
	7	4.78	770	X	X	
	8	4.80	2200			
	9	6.19	1650	X		
	10	6.47	1650	X	X	
207	--------	--------	5	--------	--------	--------
	1	.64	82	X	X	
	2	.83	2300			
	3	1.31	53	X	X	X
	4	1.85	35	X	X	X
	5	3.56	110	X	X	X
	6	4.74	390	X	X	X
	7	4.76	1550			
	8	6.37	340	X	X	X
	9	9.57	1550	X		
208	--------	--------	15	--------	--------	--------
	1	.64	400			
	2	1.03	1090			
	3	1.38	205	X	X	X
	4	2.78	3800			
209	--------	--------	5	--------	--------	--------
	1	.50	840			
	2	.67	388			
	3	1.08	122	X	X	X
	4	1.48	71	X	X	X
210	--------	--------	12	--------	--------	--------
	1	1.05	650	X		
	2	1.41	90	X	X	X
	3	2.77	1240	X		
211	--------	--------	5	--------	--------	--------
	1	.59	425			
	2	.64	685			
	3	1.00	355	X	X	
	4	1.47	70	X	X	X
212	--------	--------	6	--------	--------	--------
	1	.62	800			
	2	1.47	65	X	X	X
	3	1.87	90	X	X	X
	4	2.39	2950			

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator		
					Butler	
				Hartley	12AT7	12AU7
213	--------	--------	5	--------	--------	--------
	1	1.26	705	X	X	X
	2	1.39	700			
	3	1.67	90	X	X	X
214	--------	--------	8	--------	--------	--------
	1	.55	2200			
	2	1.18	185	X	X	X
	3	1.59	545			
215	--------	--------	5	--------	--------	--------
	1	.32	460			
	2	1.06	83	X	X	X
	3	1.67	18	X	X	X
	4	1.82	1045			
	5	2.12	30	X	X	X
	6	2.48	1000			
	7	3.33	1680			
	8	3.51	1000			
	9	3.54	620	X		
	10	3.74	100	X	X	X
	11	4.12	2800			
	12	4.83	770	X	X	
	13	4.87	800			
	14	5.02	3250			
	15	6.22	1000	X	X	
	16	6.45	1090	X	X	
216	--------	--------	6	--------	--------	--------
	1	.61	650			
	2	1.04	255	X	X	
	3	1.43	83	X	X	
	4	3.02	2400			
217	--------	--------	5	--------	--------	--------
	1	.65	1000			
	2	1.14	162	X	X	X
	3	3.07	85	X	X	X
218	--------	--------	5	--------	--------	--------
	1	.47	460			
	2	.67	70	X	X	X
	3	1.03	840			
	4	1.40	1680			
	5	2.82	1410	X	X	
219	--------	--------	5	--------	--------	--------
	1	1.03	460	X		
	2	1.45	88	X	X	X

Crystal No.	Spurious No.	f in %	Resistance ohms	Detected in Oscillator Hartley	Butler 12AT7	12AU7
220	--------	--------	11	--------	--------	--------
	1	.50	2000			
	2	.65	475			
	3	1.04	565	X		
	4	1.38	162	X	X	X
221	--------	--------	5	--------	--------	--------
	1	.75	178	X	X	
	2	1.24	36	X	X	X
	3	1.74	58	X	X	X
	4	2.95	1820	X		
	5	3.36	270	X	X	X
	6	4.45	2800			
	7	4.56	620	X	X	
	8	4.70	2950			
222	--------	--------	5	--------	--------	--------
	1	.56	705			
	2	1.19	44	X	X	X
	3	1.69	68	X	X	X
	4	3.27	195	X	X	X
	5	4.42	500	X	X	X
	6	4.88	2100			
223	--------	--------	5	--------	--------	--------
	1	.57	95			
	2	.73	475			
	3	1.13	135	X	X	X
	4	1.45	3250			
	5	1.62	100	X	X	X
224	--------	--------	7.5	--------	--------	--------
	1	.54	170			
	2	.70	595			
	3	1.12	303	X	X	
	4	1.30	2500			
	5	1.58	95	X	X	X
225	--------	--------	10	--------	--------	--------
	1	.98	225	X	X	
	2	1.44	68	X	X	X
	3	2.97	3050			
226	--------	--------	6	--------	--------	--------
	1	.39	320			
	2	.77	3250			
	3	1.25	30	X	X	X
	4	1.88	46	X	X	X
	5	3.11	705	X		

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator Hartley	Butler 12AT7	12AU7
	6	3.12	1130			
	7	3.51	155	X	X	X
	8	4.79	255	X	X	X
	9	5.95	2300			
	10	6.05	595	X	X	X
	11	6.45	650	X	X	X
	12	9.35	1360	X		
227	--------	--------	13	--------	--------	--------
	1	.62	355			
	2	1.04	270	X	X	
	3	1.49	74	X	X	X
228	--------	--------	7	--------	--------	--------
	1	1.15	75	X	X	X
	2	1.69	88	X	X	X
	3	3.17	388	X	X	X
	4	4.32	1190	X	X	
229	--------	--------	5	--------	--------	--------
	1	.56	520			
	2	.71	2200			
	3	1.16	225	X	X	
	4	1.27	1200			
	5	1.55	135	X	X	X
230	--------	--------	6	--------	--------	--------
	1	1.24	162	X	X	X
	2	1.66	91	X	X	X
	3	3.39	1000	X	X	
	4	4.31	1090	X	X	
231	--------	--------	3	--------	--------	--------
	1	.96	240	X	X	
	2	1.39	84	X	X	X
232	--------	--------	6	--------	--------	--------
	1	.49	1090			
	2	.68	270			
	3	1.05	355	X		
	4	1.43	80	X	X	X
	5	2.72	3050			
233	--------	--------	5	--------	--------	--------
	1	.46	2200			
	2	.62	3250			
	3	1.02	336	X	X	
	4	1.37	92	X	X	X
	5	2.84	1540	X		

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator Hartley	Butler 12AT7	12AU7
234	--------	--------	9	--------	--------	--------
	1	.59	255			
	2	.79	255	X	X	
	3	1.31	135	X	X	X
	4	1.47	1680			
	5	1.73	62	X	X	X
	6	2.10	2800			
235	--------	--------	16	--------	--------	--------
	1	.73	285			
	2	1.55	78	X	X	X
	3	2.05	240			
	4	2.29	3050			
236	--------	--------	10	--------	--------	--------
	1	.40	3350			
	2	.60	705			
	3	.94	1360			
	4	1.33	135	X	X	X
237	--------	--------	8	--------	--------	--------
	1	.57	2000			
	2	.96	910			
	3	1.31	162	X	X	X
238	--------	--------	3	--------	--------	--------
	1	.59	1540			
	2	.97	500	X		
	3	1.32	95	X	X	X
239	--------	--------	6	--------	--------	--------
	1	.52	388			
	2	.71	1460			
	3	1.15	62	X	X	X
	4	1.63	88	X	X	X
	5	2.79	2500			
	6	3.14	545	X	X	X
	7	4.22	2200			
240	--------	--------	8	--------	--------	--------
	1	.68	336			
	2	1.48	38	X	X	X
	3	1.64	3650			
	4	1.92	49	X	X	X
	5	3.26	270	X	X	X
	6	3.48	225	X	X	X
	7	4.42	1000	X		
	8	5.83	2950			
	9	6.08	3650			

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator Hartley	Butler 12AT7	12AU7
241	--------	--------	6	--------	--------	--------
	1	.43	1600			
	2	.97	565			
	3	1.31	135	X	X	X
242	--------	--------	5	--------	--------	--------
	1	1.03	460	X		
	2	1.38	162	X	X	X
243	--------	--------	6	--------	--------	--------
	1	.57	3050			
	2	.87	1410			
	3	1.20	178	X	X	X
244	--------	--------	7	--------	--------	--------
	1	.49	255			
	2	.60	178	X	X	
	3	.97	2300			
	4	1.35	2400			
245	--------	--------	5	--------	--------	--------
	1	.58	2400			
	2	.99	240	X	X	
	3	1.38	92	X	X	X
246	--------	--------	6	--------	--------	--------
	1	.44	1360			
	2	.63	2300			
	3	.92	255	X	X	
	4	1.34	95	X	X	X
247	--------	--------	6	--------	--------	--------
	1	.47	2200			
	2	.64	425			
	3	1.08	195	X	X	
	4	1.19	3250			
	5	1.49	135	X	X	X
248	--------	--------	7	--------	--------	--------
	1	.63	255			
	2	.81	1300			
	3	1.33	98	X	X	X
	4	1.72	92	X	X	X
249	--------	--------	6	--------	--------	--------
	1	.61	2400			
	2	.78	595			
	3	1.19	255	X	X	
	4	1.55	105	X	X	X

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator Hartley	Butler 12AT7	12AU7
250	----------	----------	6	----------	----------	----------
	1	1.80	41	X	X	X
	2	2.33	44	X	X	X
	3	3.26	3250			
	4	3.77	2800			
	5	4.10	210	X	X	
	6	4.27	95	X		X
	7	5.25	425	X	X	
	8	5.29	960			
	9	5.38	1410			
	10	5.59	3250			
	11	6.43	2000	X		
	12	6.45	3650			
	13	6.65	650	X	X	X
	14	6.95	2650			
	15	7.86	3650			
	16	7.96	2650	X		
251	----------	----------	5	----------	----------	----------
	1	.47	2950			
	2	1.10	100	X	X	X
	3	1.20	1680			
	4	1.51	90	X	X	X
	5	3.74	2650			
252	----------	----------	28	----------	----------	----------
	1	.53	1190			
	2	.67	285	X	X	
	3	1.23	100	X	X	X
	4	1.33	910			
	5	1.72	90	X	X	X
	6	3.05	2200			
	7	3.52	195	X	X	X
	8	4.84	371	X	X	X
	9	4.82	2200			
	10	6.12	2400			
	11	6.33	770	X	X	
	12	6.38	910			
	13	6.50	2950			
	14	8.34	1750			
	15	9.53	1680	X		
253	----------	----------	6	----------	----------	----------
	1	.68	100	X	X	
	2	1.36	46	X	X	X
	3	1.95	58	X	X	X
	4	3.32	1680			
	5	3.64	100	X	X	X
	6	4.90	285	X	X	X
	7	6.32	1000	X		
	8	6.50	336	X	X	X
	9	8.65	1080	X	X	
	10	9.77	1680	X		
	11	9.83	1360	X		
	12	11.90	1750	X		
254	----------	----------	7	----------	----------	----------
	1	.76	135	X	X	X
	2	1.27	500			
	3	1.51	100	X	X	X
	4	2.93	3250			
255	----------	----------	5	----------	----------	----------
	1	.50	910			
	2	.67	445			
	3	1.13	75	X	X	X
	4	1.25	3350			
	5	1.57	93	X	X	X
	6	2.71	3350			
	7	3.05	371	X	X	X
	8	3.96	2950			
256	----------	----------	5	----------	----------	----------
	1	.66	55	X	X	X
	2	1.10	70	X	X	
	3	1.47	55	X	X	X
	4	2.90	910	X	X	
	5	3.75	3250			
257	----------	----------	5	----------	----------	----------
	1	.46	2800			
	2	.69	2400			
	3	1.08	55	X	X	X
	4	1.71	53	X	X	X
	5	2.80	2200			
	6	3.16	178	X	X	X
	7	4.59	320	X	X	X
	8	5.55	2650			
	9	5.96	1410	X	X	
258	----------	----------	7	----------	----------	----------
	1	.61	3250			
	2	.78	910			
	3	1.30	98	X	X	X
	4	1.63	122	X	X	X
259	----------	----------	6	----------	----------	----------
	1	.58	84	X	X	
	2	.70	1240			
	3	1.14	210	X	X	X
	4	1.57	170	X	X	X

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator		
				Hartley	Butler 12AT7	12AU7
260	----------	----------	8	----------	----------	----------
	1	.64	149			
	2	.81	100	X	X	X
	3	1.25	270			
	4	1.62	142	X	X	X
	5	2.97	3250			
261	----------	----------	5	----------	----------	----------
	1	.46	3250			
	2	.62	3250			
	3	1.07	100	X	X	X
	4	1.46	178	X	X	X
262	----------	----------	5	----------	----------	----------
	1	.47	3250			
	2	.64	1820			
	3	1.08	95	X	X	X
	4	1.19	3650			
	5	1.48	84	X	X	X
263	----------	----------	7	----------	----------	----------
	1	.63	960			
	2	.79	1410			
	3	1.28	77	X	X	X
	4	1.66	186	X		
264	----------	----------	7	----------	----------	----------
	1	.43	500			
	2	1.04	100	X	X	X
	3	1.45	84	X	X	X
	4	2.90	650	X	X	X
265	----------	----------	10	----------	----------	----------
	1	.56	303			
	2	.73	2400			
	3	1.22	79	X	X	X
	4	1.68	74	X	X	X
	5	2.90	3650			
	6	3.14	910	X	X	
	7	4.10	1460	X	X	
266	----------	----------	7	----------	----------	----------
	1	.41	303			
	2	.56	2500			
	3	1.01	88	X	X	X
	4	1.42	90	X	X	X
	5	2.88	705	X	X	X
	6	3.77	2500			

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator		
				Hartley	Butler 12AT7	12AU7
267	----------	----------	8	----------	----------	----------
	1	.59	3250			
	2	.79	1410			
	3	1.23	142	X	X	X
	4	1.37	1300			
	5	1.58	79	X	X	X
	6	3.43	2000	X		
268	----------	----------	6	----------	----------	----------
	1	.59	705			
	2	.76	388			
	3	1.21	90	X	X	X
	4	1.58	100	X	X	X
269	----------	----------	6	----------	----------	----------
	1	1.22	135	X	X	X
	2	1.60	135	X	X	X
270	----------	----------	8	----------	----------	----------
	1	1.05	100	X	X	X
	2	1.13	2200			
	3	1.45	200	X	X	X
	4	5.43	3650			
271	----------	----------	8	----------	----------	----------
	1	1.11	49	X	X	X
	2	1.65	35	X	X	X
	3	1.97	3650			
	4	2.90	1360			
	5	3.25	122	X	X	X
	6	4.27	225	X	X	X
	7	4.53	1300			
	8	5.73	2950			
	9	5.99	1900			
	10	6.02	595	X	X	X
	11	6.17	1190			
	12	7.52	1090	X	X	
	13	7.95	1410	X	X	
	14	9.90	1460	X		
	15	10.08	960	X		
	16	11.60	1820	X		
272	----------	----------	6	----------	----------	----------
	1	.63	320			
	2	.84	135	X	X	
	3	1.28	95	X	X	X
	4	1.44	1300			
	5	1.69	84	X	X	X

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator Hartley	Butler 12AT7	Butler 12AU7
274	----------	----------	10	----------	----------	----------
	1	.69	1300			
	2	1.02	220	X	X	
	3	1.48	95	X	X	X
	4	3.04	4700			
275	----------	----------	6	----------	----------	----------
	1	.46	170			
	2	.64	2300			
	3	1.02	240	X	X	
	4	1.52	75	X	X	X
276	----------	----------	10	----------	----------	----------
	1	.47	2650			
	2	.61	100	X	X	X
	3	.98	770			
	4	1.25	336	X	X	X
	5	2.76	4100			
277	----------	----------	6	----------	----------	----------
	1	1.31	94	X	X	X
	2	1.43	3050			
	3	1.72	97	X	X	X
	4	5.52	3900			
278	----------	----------	6	----------	----------	----------
	1	.50	870			
	2	.75	1190			
	3	1.17	95	X	X	X
	4	1.34	2950			
	5	1.72	68	X	X	X
	6	1.83	3250			
	7	2.93	2950			
	8	3.24	336	X	X	X
	9	4.33	705	X	X	
	10	5.88	2650			
279	----------	----------	7	----------	----------	----------
	1	.67	1190			
	2	1.04	565	X		
	3	1.37	100	X	X	X
	4	2.61	2200			
280	----------	----------	220	----------	----------	----------
	1	.47	1820			
	2	1.01	1240	X		
	3	1.32	360	X	X	X
281	----------	----------	7	----------	----------	----------
	1	1.11	108	X	X	X
	2	1.54	85	X	X	X

Crystal No	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator Hartley	Butler 12AT7	Butler 12AU7
282	----------	----------	7	----------	----------	----------
	1	1.05	149	X	X	X
	2	1.16	3250			
	3	1.56	83	X	X	X
	4	3.09	445	X	X	
	5	4.22	910	X	X	
283	----------	----------	5	----------	----------	----------
	1	.59	620			
	2	1.20	77	X	X	X
	3	1.57	122	X	X	X
	4	3.36	3650			
284	----------	----------	11	----------	----------	----------
	1	.67	500			
	2	1.17	77	X	X	X
	3	1.26	1540			
	4	1.58	67	X	X	X
	5	2.23	2100			
	6	3.04	545	X	X	X
	7	4.05	2200			
285	----------	----------	5	----------	----------	----------
	1	.53	500			
	2	1.20	40	X	X	X
	3	1.68	72	X	X	X
	4	2.79	595	X		
	5	3.11	425	X	X	X
	6	4.12	1000	X	X	
286	----------	----------	5	----------	----------	----------
	1	.62	240			
	2	1.02	270	X	X	
	3	1.40	78	X	X	
	4	2.74	1600	X		
287	----------	----------	9	----------	----------	----------
	1	1.11	88	X	X	X
	2	1.56	100	X	X	X
	3	2.99	1090	X	X	
288	----------	----------	10	----------	----------	----------
	1	.67	100	X		
	2	.82	840			
	3	1.38	78	X	X	X
	4	1.80	77	X	X	X
289	----------	----------	5	----------	----------	----------
	1	.59	68	X	X	X

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator		
				Hartley	Butler 12AT7	12AU7
	2	.91	1820			
	3	1.26	685			
	4	2.59	1460	X	X	
290	--------	--------	5	--------	--------	--------
	1	1.13	122	X	X	X
	2	1.51	81	X	X	X
	3	5.30	2400			
291	--------	--------	5	--------	--------	--------
	1	.74	320			
	2	1.25	140	X	X	X
	3	1.58	108	X	X	X
292	--------	--------	8	--------	--------	--------
	1	1.002	162	X	X	
	2	1.09	2400			
	3	1.40	135	X	X	X
293	--------	--------	6	--------	--------	--------
	1	.49	1750			
	2	1.14	95	X	X	X
	3	1.55	88	X	X	X
	4	2.66	2000			
294	--------	--------	65	--------	--------	--------
	1	.65	1045			
	2	1.02	303	X	X	
	3	1.40	100	X	X	X
	4	2.64	2400			
295	--------	--------	6	--------	--------	--------
	1	1.08	400	X		
	2	1.61	64	X	X	X
296	--------	--------	5	--------	--------	--------
	1	.65	58	X	X	X
	2	1.05	225			
	3	1.40	162	X	X	X
297	--------	--------	95	--------	--------	--------
	1	.39	870			
	2	.56	215	X	X	
	3	.85	1090			
	4	1.20	355	X	X	X
	5	2.44	1540	X	X	
298	--------	--------	7	--------	--------	--------
	1	.70	84	X	X	X

Crystal No.	Spurious No.	f in %	Resistance & ohms	Detected in Oscillator		
				Hartley	Butler 12AT7	12AU7
	2	1.05	210			
	3	1.40	85	X	X	X
299	--------	--------	6	--------	--------	--------
	1	.71	400			
	2	1.08	290	X	X	
	3	1.53	69	X	X	X
300	--------	--------	11	--------	--------	--------
	1	.50	371			
	2	.80	100	X	X	X
	3	1.17	303			
	4	1.47	108	X	X	X

B. Analysis

In the first crystal tested, #201, the effect of the "Q" of the tuned circuit (the bandwidth of the oscillator) became very apparent. The Butler oscillator incorporating the 12AT7 vacuum tube, by virtue of a higher plate resistance than a 12AU7, was able to detect the 185 ohm spurious (#2) which was located between a 91 ohm spurious (#4) and a main mode series resistance of 7 ohms. The same oscillator using a 12AU7 vacuum tube was not able to detect this spurious. The only factor involved in this case is the selectivity of the circuits since the gain in all three circuits will easily allow oscillations on a 185 ohm spurious.

Of the 100 crystals tested, the 12AU7 Butler circuit oscillated on spurious as high as 705 ohms in crystals #213 and 266. The 12AT7 Butler circuit oscillated on a spurious resistance as high as 1650 ohms in crystal #206. The Hartley circuit oscillated on a 2650 ohm spurious in crystal #250.

The greater selectivity attainable with a Hartley oscillator is apparent in the results of crystal #206. Spurious #5, whose resistance is 920 ohms, was detected only by the Hartley oscillator. This spurious was picked out from in between a 70 and 240 ohm spurious by this oscillator. The 12AT7 Butler was incapable of selecting this spurious and went from spurious #4 directly to spurious #6. The gain of the 12AT7 Butler oscillator was obviously sufficient since it detected the spurious #10 resistance of 1650 ohms.

The results obtained with the Hartley oscillator are displayed graphically in Fig. 5. The curve, which has been obtained from the experimental points, shows the maximum values of spurious resistances detectable throughout the frequency range. It is only possible to utilize a few points since, in the majority of cases, when a high R spurious was present, the oscillations were controlled by a lower R spurious in the immediate vicinity. In the upper region of the curve (above 2% Δf) the curve is almost representative of the maximum values of R's which may control oscillations. In the immediate vicinity of the main mode frequency the actual ability of the oscillator is never utilized since there are always lower R spurious responses present. To obtain a more accurate plot in the vicinity of the main response the simulated spurious technique was utilized.

For the simulated spurious technique the main response was obtained by the use of a crystal that had no detectable spurious responses. In shunt with this crystal was placed a series circuit consisting of a crystal, whose main response was within 1% of the spurious free crystal frequency, and a resistor. This resistor was varied to determine the value at which oscillations would no longer occur. The results of this test are shown in Fig. 6. As in Fig. 5, the circles indicate responses that were detected and the triangles responses which were not detected. In Fig. 6 all of the responses of the crystals within 1% were plotted. In Fig. 5 however, only the pertinent values in the region of the curve were utilized to minimize confusion. It must be realized that if all the points would appear on the curve of Fig. 5 there would be many triangles below the curve but no circles would appear above the curve. The triangles below the curve were left out for reasons of clarity since the only reason they were not detected was due to the presence of lower R spurious modes in the immediate vicinity.

IV POWER DETERMINATION

The power dissipated in a crystal may be determined in a number of ways. If the R.F. current through the crystal at its series resonant frequency is known and the resistance of the main mode has been determined, the power may be computed by the I^2R method. If the voltage across the crystal at series resonance is known and the resistance of the main response has been determined, the power may be computed by the E^2/R method.

A. Butler Oscillator

During the investigation of the Butler crystal oscillator of Fig. 1 both methods were tried. For the following tests a variable 0 to 500 ohm AC load was placed across R_3. This load was varied to obtain an R.F. voltage of .5 volts across R_3 as measured by a Ballantine AC meter. The tank circuit was then tuned through resonance and the DC voltages appearing at the Crystal Current terminal and the R.F. Indicator terminal were recorded. The following results were obtained.

Voltage across crystal - .2 - .4 - .29 - .33 - .43
Voltage across R_8 - .26 - .36 - .49 - .49 - .42

It may be noted that the point of resonance is indicated by a minimum crystal current as well as a maximum output voltage at the crystal series resonant frequency.

It may be seen that the voltage across R_3 also appears across the series combination of the crystal resistance and R_8. That is to say that the current which flows through the crystal also flows through R_8. Therefore, by measuring the voltage across R_8 and dividing by the R.F. impedance from the cathode (pin 8) to ground, the current flowing through the crystal may be obtained. The R.F. impedance across the resistor R_8 is equal to the resistance R_8 in parallel with the sum of the tube plate resistance and the tank impedance divided by the sum of the amplification factor of the tube plus 1. This calculation yields an R.F. load in the cathode of the grounded grid amplifier of 240 ohms. In the previous data it was seen that the maximum output voltage across this R.F. cathode load was .49 volt. Dividing .49 by 240 gives a crystal current of 2.0 milliamperes. The resistance of this crystal (#201) is 7 ohms, from Table II. The power dissipated in the crystal may now be calculated as .03 milliwatt. The voltage drop across the crystal may be calculated by multiplying the 2 milliampere current by the 7 ohm crystal resistance, giving 14 millivolts. Adding this to the .49 volt across R_8 gives a voltage across R_3 of .504 volt. This agress with the original setting of .5 volt. The 14 millivolts dropped across the crystal is far different, however, from the 290 millivolts obtained by direct measurement.

To determine if the voltage across the crystal was a function of the current at all, the AC load across R_8 was changed. The load was first changed from 240 to 127 ohms resulting in the same voltage across

this cathode impedance; but the 290 millivolts across the crystal was raised to 410 millivolts. When the AC load across R_8 was changed to 100 ohms the voltage across the crystal was raised to 540 millivolts while the voltage across R_8 remained the same, .49 volt. At this point resistors were substituted for the crystal until the value was found which would give the same output voltage as the crystal. This value turned out to be few hundred ohms rather than the 7 ohms of the crystal. A value of resistance was then found which would give the same value of voltage across the resistance that had previously been measured across the crystal. This value was again different but also in the hundreds of ohms. These experiments were duplicated with B+ voltages of 150 and 105 volts with the same end results. At this point experiments on the Hartley oscillator were begun and the remainder of the power determination experiments were performed on that oscillator.

B. Hartley Oscillator

The methods of measuring power in the Hartley oscillator are identical to those explained for the Butler oscillator. That is, the current through the crystal or the voltage across the crystal must be determined and either one utilized in conjunction with the main mode series R to calculate the dissipated power. Since the current flowing through the crystal is now applied to the tank circuit there is no simple way of measuring the crystal current. For this reason the voltage across the resistor R_1 is used to calculate the current. R_1 is a plug-in resistor which may be interchanged with the crystal allowing voltages across the crystal to be measured.

With the potentiometer, R_8, (See Fig. 2) adjusted for maximum oscillator exitation, the output voltage measured at the R.F. Indicator terminal is 3 volts and the voltage across the resistor R_1 is 84 millivolts. The crystal is removed from its socket and resistors substituted until a value is found which produces the same output voltage. This value of resistance is 120 ohms, which gives a voltage across R1 of 275 millivolts. If the 84 millivolts measured across the 100 ohm resistor is any indication of the current through the crystal, the power dissipated in the crystal is only a few microwatts. However, since the actual operating conditions cannot be simulated by substituting resistances for the crystal, this value of measured current cannot be considered valid. A possible reason for the inconsistencies of the resistance substitution method may be due to nonlinearities. In an effort to obtain pure class-A operation, the screen exitation voltage was decreased in steps and the resistance substitution method tried in each case. The results are shown in Table III.

TABLE III

Resistance Substitution Tests

Screen Volts	Output Volts	MV Across 100 ohm res.	Resistance for same voltage out	MV across 100 ohm res.
110	3.0	84	120	275
100	2.5	64	120	205
90	2.13	52	150	148
80	1.7	36	120	112
70	1.37	26	135	65
60	1.02	15.8	135	36
50	.68	8.4	150	13
45	.48	4.3	68	7.6
40	.34	2.3	9	4.0
35	.22	1.0	?	1.1

The column entitled Output Volts is the voltage measured at the R.F. Indicator terminal. The third column is the voltage measured at the Crystal Current terminal, the voltage across the 100 ohm resistor

R_1 with the crystal in place. The last column is the same voltage but with the value of resistance indicated in column four in place of the crystal. The results remain fairly inconsistent as the exitation is decreased until the screen voltage drops to about 45 volts. At about 40 volts of screen voltage the resistor which must be substituted for the crystal to obtain the same output voltage actually approaches the series resistance of the crystal itself. However, the voltage across R_1 is measured as 4 millivolts with the resistor in place and only 2.3 millivolts with the crystal in place. When the screen voltage is dropped to 35 volts the output voltage with the crystal in place is .22 volt. This voltage is not obtainable with even a short circuit in place of the crystal, the highest output obtainable being .17 volt.

C. Measuring Techniques

The voltage measured at the R.F. indicator terminal in the oscillators of Figs. 1,2, and 3 is primarily used as an indication of oscillation. However, in the case that the actual R.F. voltage is required, as in the case of the Butler oscillator, the R.F. voltage may be obtained from the calibration curve of Fig. 4. By the use of this curve an R.F. voltage in the range of 40 millivolts to .8 volt may be determined. The DC voltage in this case was measured with a "Millivac".

The indications obtained by measuring the voltage across a resistor placed in series with the crystal always tend to be much too high. Since the method used to measure the voltage across this series resistor responds to peak values of voltage, it is possible that these high readings are due to some form of nonlinearity such as might be obtained by class-B or class-C operation; or when blocking oscillations are taking place at a much lower frequency.

In order to determine the cause and extent of the nonlinearities, the waveform was observed in both oscillators with a high frequency Tektronix oscilloscope.

The Hartley oscillator, when using a crystal in series with a 100 ohm resistor, showed a slight amount of distortion at high drive levels. A 300 ohm resistor was substituted for the crystal which gave the same value of output voltage at the R.F. Indicator terminal. The behavior was similar in that the waveform became slightly distorted at higher drive levels. However, the distortion was more the limiting type rather than the nonlinear type which occurred in the case of the crystal. When smaller values of resistances were substituted for the crystal the oscillator began to block. This blocking could have also been observed by increasing the exitation from zero while observing the output voltage. At the point that blocking oscillations begin the output voltage increases sharply.

Since the Butler oscillator had no built-in exitation control it was decided to obtain a variation in the drive level by varying the tuning. This was successfully accomplished. The oscillator in this case was the Symmetrical Butler oscillator of Fig. 3. When a crystal was placed in series with a 100 ohm resistor the output voltage was .44 volt. By approaching oscillations from a lower frequency, the output voltage could be continuously varied. Up to a value of .06 volt output which could also be obtained by replacing the crystal with a 2200 ohms resistor, the waveform appeared to be purely sinusoidal. However, when the output voltage was increased beyond this point the output waveform definitely became distorted. At the point of maximum

output the waveform was extremely distorted. In each case it was possible to simulate the output voltage and distortion by replacing the crystal with a resistor. When this value was 180 ohms a critical point had been reached. At any value of resistance below 180 ohms blocking oscillations were observed. The waveform observed at the grid of the cathode follower stage indicated that the RC coupling network between the tank circuit of the grounded-grid amplifier and the grid of the cathode follower was the cause of the blocking oscillations.

Conclusions

The three crystal oscillators which were used to obtain the data of Table II were successful, to some degree, in detecting the spurious responses of crystals. The Hartley oscillator was more sensitive and more selective than either version of the Butler oscillator. This was principally due to the tank circuit being in the grid of the cathode follower where the loading is very light. In the Butler oscillator the selective circuit being used as a plate impedance is subject to loading by the plate resistance of the amplifier tube. The Hartley circuit has the added advantage of an easily incorporated exitation control by varying the screen potential.

Of the two Butler oscillators used to obtain the test data, the one incorporating the 12AT7 vacuum tube was both more sensitive and more selective than the same circuit incorporating a 12AU7 vacuum tube. The greater selectivity was due to the higher value of plate resistance 12AT7 causing less loading on the tank circuit and retaining a higher value of "Q". The greater sensitivity is due to the realization of a higher gain in the grounded grid amplifier stage.

The conclusion may now be drawn, at least for this range of frequencies, that the Hartley oscillator best performs the function of detecting spurious responses. However, it is very possible that the sensitivity and selectivity of this oscillator may be too great. When it is realized that out of 100 perfectly useable normal production run crystals, about 90 to 95 would have detectable spurious, the thought must occur that this oscillator may be too good. In order to determine just how much ability this oscillator should have it would be necessary to compute the value of limiting R and the bandwidth of the circuit for every oscillator currently in use and then use a detecting oscillator which responds to a higher value of limiting R and has a narrower bandwidth than any of these using oscillators. Deciding just how much selectivity and sensitivity is required will be left for a later date.

From the results obtained in preliminary attempts to measure power dissipation in the crystal, it appears that the drive levels must be raised to reach the 20 milliwatt level required. The main problem encountered with measuring power dissipated in the crystal when used in a detecting oscillator is that of extraneous blocking or parasitic oscillations.

Due to the high "Q's" incorporated in most of these oscillator circuits, the higher impedance levels have made regeneration a problem. This means that the physical layout will be critical and must be well planned.

Program for Next Interval

A Butler and a Hartley oscillator for use at 30 and 50 Mc. will be developed and evaluated. Based on the performance of these oscillators, one circuit will be chosen for the final instrument.

The number of oscillators required to cover the frequency range will be determined. These will be constructed as separate units and then evaluated.

A "bridge" method of compensating for the effect of the crystal shunt capacity will be investigated. Only by this means will it be possible to achieve compensation over a large frequency range.

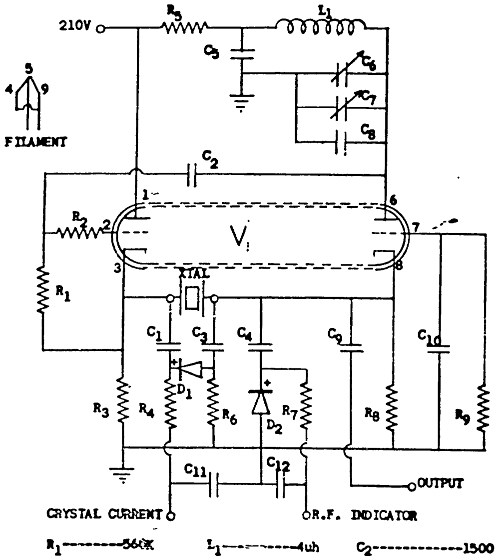
Identification of Personnel

1. Robert D. Vann - 542 manhours during third quarter.
   Technician
2. Joseph Loos - 276 manhours during third quarter.
   Engineer, Senior Electronic Development.

FIGURE - 1

BUTLER CRYSTAL OSCILLATOR

6-7 MEGACYCLES



R_1---------560K

R_2---------27

$R_3R_4R_6$-----10K

R_5---------39K

R_7R_9------1 Meg.

R_8---------270

L_1-----------4uh

D_1D_2---------1N34

V_1-----------12AU7

$C_1C_3C_4$------200

C_2------------1500

$C_5C_{10}C_{11}C_{12}$---.01uf

C_6 - 7 to 47 Air Var.

C_7 - 7 to 45 Cer. Trim.

C_8-------------75

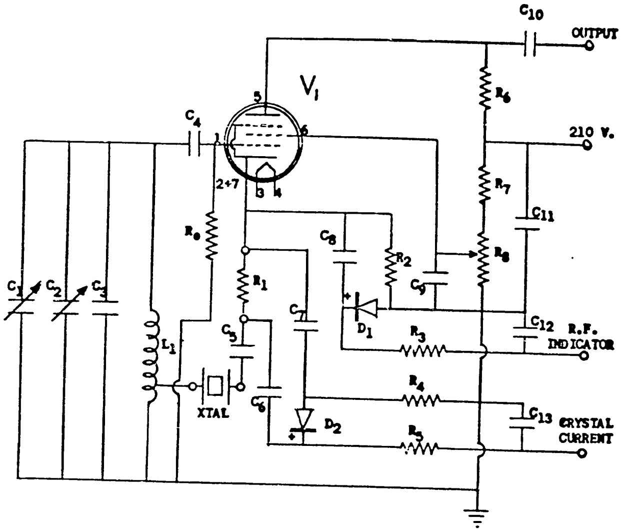
C_9-------------25

ALL RESISTANCE IN OHMS. ALL CAPACITANCES IN UUF UNLESS OTHERWISE MARKED.

FIGURE -

HARTLEY SERIES MODE CRYSTAL OSCILLATOR

6-7 MEGACYCLES



R_1----------100

R_2----------470

R_0 - R_3----1 Meg.

R_4 R_5------10K

R_6----------12K

R_7----------47K

R_8----------500K Pot

L_1--------------4u.H.

D_1D_2------------1N34

V_1--------------6AK5

C_1 7 to 47----Air Var.

C_2 7 to 45----Cer. Trim

C_3-------------75

$C_4C_6C_7C_8$------200

$C_5C_9C_{11}$--------.01uf

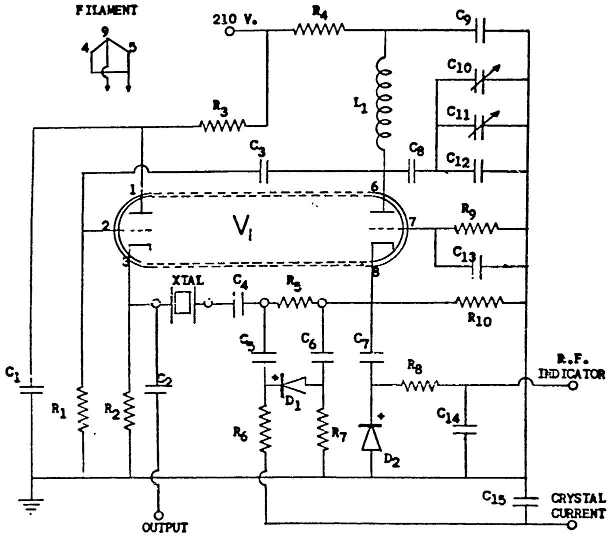
$C_{10}C_{12}C_{13}$-----.0015uf

ALL RESISTANCES IN OHMS. ALL CAPACITANCES IN UUF UNLESS OTHERWISE MARKED.

FIGURE - 3

SYMMETRICAL BUTLER OSCILLATOR

6-7 Megacycles



R_1---------560K
R_2R_{10}------270
$R_3R_4R_6R_7$---10K
R_8R_9-------1 Meg.
R_5---------100
L_1---------4uH

V_1-----------------12AU7
D_1D_2--------------1N34
$C_1C_9C_{13}C_{14}C_{15}$-------.01uf
C_2-----------------25

C_3------------------100
C_4C_8----------------1500
$C_5C_6C_7$--------------200
C_{10} 7 to 47----Air Var.
C_{11} 7 to 45----Cer. Trim
C_{12}------------------75

ALL RESISTANCES IN OHMS, ALL CAPACITORS IN UUF UNLESS OTHERWISE MARKED.

FIGURE - 4

CALIBRATION CURVE FOR R.F. PROBES

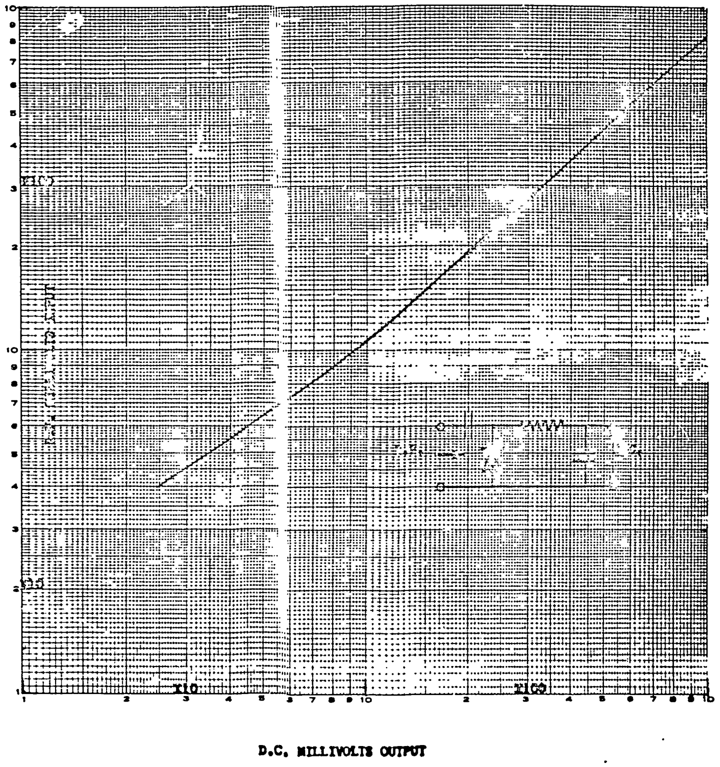


FIGURE - 5

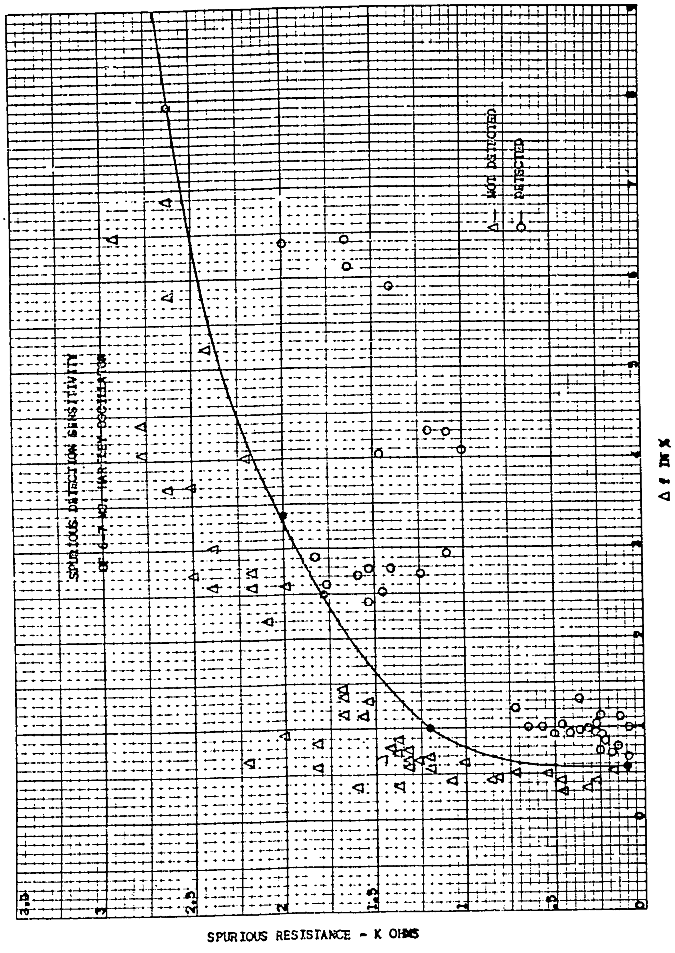


FIGURE - 6

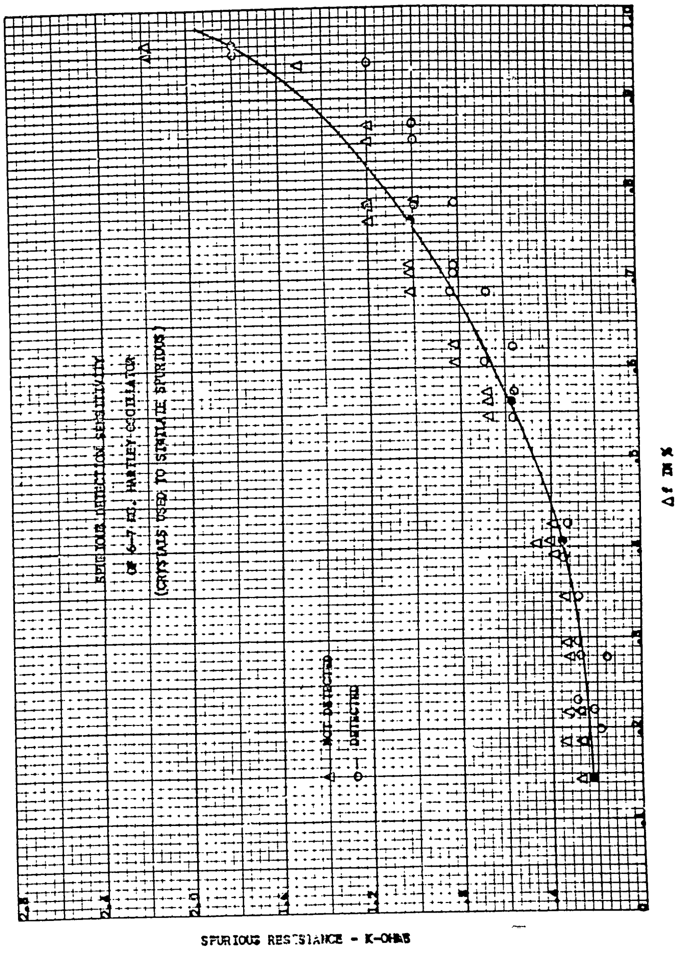
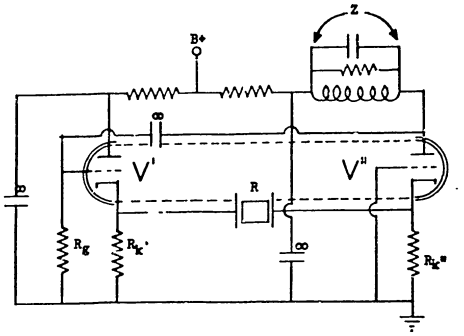
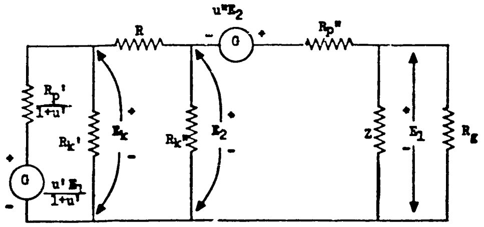


FIGURE - 8

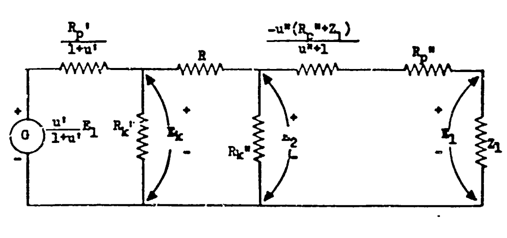
BUTLER OSCILLATOR



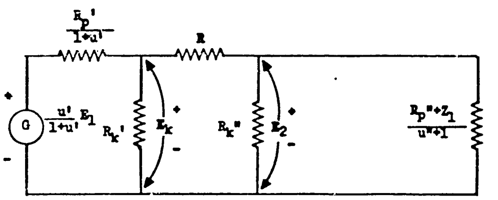
(a) SCHEMATIC



(b) EQUIVALENT CIRCUIT



(c) EQUIVALENT CIRCUIT



(d) EQUIVALENT CIRCUIT

NOTE:

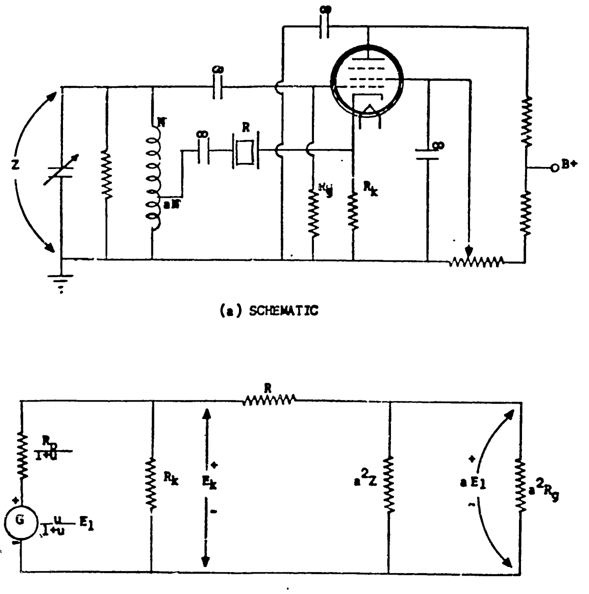
R_p = A.C. plate resistance of tube

u = amplification factor of tube

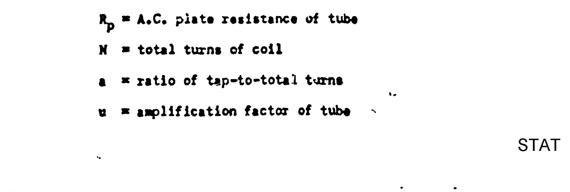
$Z_1 = \frac{ZR_g}{Z+R_g}$

FIGURE - 7

HARTLEY OSCILLATOR



(a) SCHEMATIC



(b) EQUIVALENT CIRCUIT

NOTE:

R_p = A.C. plate resistance of tube

N = total turns of coil

a = ratio of tap-to-total turns

u = amplification factor of tube

STAT