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Charles D. Preston

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A RADIO FREQUENCY POWER OSCILLATOR AND IMPEDANCE MATCHING DEVICE - PRESTON

A RADIO FREQUENCY POWER OSCILLATOR AND IMPEDANCE MATCHING DEVICE

By

Charles D. Preston

A Thesis
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Requirements for the Degree of
Master of Science in Physics

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1963

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MASTER OF SCIENCE

W J Parish
Dean

June 1, 1963
Date

A RADIO FREQUENCY POWER OSCILLATOR AND IMPEDANCE MATCHING DEVICE

Charles D. Preston

Thesis committee

J J Green
Chairman

C. G. Lennott

Victor H. Regener

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CHAPTER I

INTRODUCTION

Certain molecules, called "globular" molecules, when first solidified form what are called "plastic" crystals. They are called "globular" either because they may exhibit an approximate spherical symmetry about their center of structure or because they may be small enough or of such a shape as to appear spherically symmetric because of rotation. The first case might be exemplified by methane (CH_4) which has the configuration of a regular tetrahedron. The second case might be exemplified by hydrogen chloride (HCl).

The crystals formed by these "globular" molecules upon solidifying are called "plastic" because of the ease with which they can flow through a hole. These crystals are almost always cubic in structure.

It is expected that these "plastic" crystals might display irregularities in their elastic stiffness constants when compared to similar ordinary molecular formed by related non-globular molecules. One such irregularity might be a much smaller elastic stiffness constant which could be shown by a correspondingly smaller velocity of sound.

In a cubic crystal longitudinal or compressional waves travel in the direction of the principal axes with a velocity

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The crystals [illegible] solidifying are [illegible] which they are first [illegible] almost always [illegible]

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In a [illegible] travel in the [illegible]

$$u = \sqrt{c_{11}/\rho} \quad ,$$

where c_{11} is the elastic stiffness constant along one of the principal axes, giving the tensional stress associated with strain in the same direction, and (ρ) is the density of the material. In the same type of crystal, transverse or shear waves travel along the principal axes with a velocity

$$u = \sqrt{c_{44}/\rho}$$

where (c_{44}) is the elastic stiffness constant along one of the principal axes, giving the shear stress associated with strain at right angles to that direction, and (ρ) is again the density of the material. A remaining special case is that of transverse waves which travel along the (110) direction with velocity

$$u = \sqrt{(c_{11} - c_{12})/2\rho}$$

where c_{12} is the elastic stiffness constant giving the tensional stress along one principle axis associated with the strain along another principal axis.

Longitudinal waves and transverse waves can be induced and detected in a crystal sample by means of X-cut and Y-cut quartz crystal transducers, respectively. The velocity of ultrasonic waves in globular samples can be measured by the interferometric method, by the pulse method, or by some combination of the two (1). Once the velocity of ultrasound is obtained, it is possible to evaluate the elastic stiffness constants of the sample by using the relationship between the velocity, the stiffness constants,

[illegible]

where e_{11} is the [illegible]

the principal axis [illegible]

with strain in the [illegible]

of the material. [illegible]

or shear waves [illegible]

velocity

[illegible]

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Longitudinal waves [illegible]

duced and detected [illegible]

and [illegible] quartz [illegible]

velocity of ultrasonic [illegible]

measured by the [illegible]

or by some [illegible]

of ultrasonic [illegible]

the elastic stiffness [illegible]

the relationship [illegible]

and the density.

The interferometric method was chosen in preference to the others because of the difficulty in obtaining a pulse with a rise time of the order of a few tenths of microseconds and with enough power to penetrate the crystal sample.

The interferometric method can be used in two ways to obtain similar results. The transmitted wave can be brought into interference with some of the incident signal which is allowed to bypass the sample, or the transmitted signal can interfere with its own echoes which result from reflections at the crystal faces.

In any case the transmitted signal is suppressed forty to sixty decibels. The attenuation is highly dependent upon the medium into which the transducer radiates. For example, a crystal with a lattice structure which may be easily distorted, such as camphene, will absorb more of the sound energy than one which has a more firm lattice structure, such as steel. Since the transmitted signal is greatly attenuated it is necessary to excite the piezo-element as vigorously as possible within the limits of the material. Therefore it is desirable to supply the piezo-element with a large amount of power.

When the transmitted wave is brought into interference with a part of the incident wave, the phase difference is determined by the transversal time of the and the density,

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microsecond [illegible]
sample.

The [illegible]
obtain [illegible]
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In any case [illegible]
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structure, [illegible]
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once is [illegible]

transmitted wave through the sample. The phase difference is

$$\Delta\phi = \omega t = \omega L/c \quad .$$

With (L) fixed, the conditions for interference depend only upon frequency; therefore, if the frequency is continuously varied, maxima and minima will occur as the phase difference passes through multiples of 2π. Let some maximum be called the m^{th}; this maximum occurs at some frequency (f_1). Another maximum, the n^{th}, will occur at a separate frequency (f_2). Then

$$\Delta\phi_1 \quad 2\pi f_1 L/c = 2\pi m$$

and

$$\Delta\phi_2 \quad 2\pi f_1 L/c = 2\pi(m+n).$$

These two relations then determine the velocity

$$c = L(f_1 - f_2)/n.$$

When the transmitted wave is brought into interference with its own reflections, the phase difference is again determined by the transversal time of the wave through the sample. In this case the phase difference is

$$\Delta\phi = \omega t = 2kL\omega/c,$$

where (k) is the number of reflections by the wave from the interface. With the distance (L) fixed, the conditions for interference depend only upon the frequency. As the frequency is continuously varied the phase difference will pass through values which are multiples of 2π. The resultant waveform may be the sum of few or of many reflections depending on the material. In a medium which greatly attenuates the signal, the order of reflection for which the echoes

no longer have sufficient amplitude to cause interference will be quite low; however in a medium which does not greatly attenuate the signal, the reflected signal may still be of sufficient amplitude to produce measurable interference after tens or hundreds of reflections (1). Let some maximum be called the m^{th}; this maximum occurs at some frequency (f_1). Another maximum, the n^{th}, will occur at some frequency (f_2). Then

$$\Delta\phi_1 \quad 2\pi f_1 \cdot 2kL/c = 2\pi m$$

and

$$\Delta\phi_2 \quad 2\pi f_2 \cdot 2kL/c = 2\pi(n+m).$$

These two relations then determine the velocity

$$c = 2kL(f_1 - f_2)/n.$$

In both cases there should be a correction because of the change of phase occuring at the interface between the quartz crystal and the sample; however, since such a phase shift has been shown to be two degrees or less (2), no attempt need be made to correct for it.

One of the primary difficulties encountered in the measurement of the velocity of ultrasound in globular crystals is that of obtaining a single crystal of large size. Here "large" means much greater than the wavelength of the mechanical vibration in the sample. The wavelength of ultrasound is directly proportional to the velocity of the ultrasound and inversely proportional to the frequency of the mechanical vibration of the sample.

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Let some [illegible]

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occur at some frequency [illegible]

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One of the [illegible]

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of the sample.

Let us assume a case in which a single crystal in the shape of a cube, each face of which is one square centimeter. Let us further assume that the velocity of ultrasound in this sample is known to be 1.4×10^3 meters per second. In the extreme, one wavelength is equal to the length of the sample. For this case the frequency must be 0.14 Mc. Therefore, frequencies of a few megacycles and larger must be employed in order to observe more than one interference maximum or minimum.

This thesis discusses the design and construction of a power radio frequency oscillator, and the transfer of power to the piezoelement from the radio frequency oscillator in order to insure sufficient mechanical vibration in the piezoelement to penetrate the length of the sample. This transmitted wave must be of large enough amplitude to be detected.

It is also desirable to have a wideband response for the piezoelement in order that more than one maximum or minimum may be observed near the resonate frequency of the piezoelement. Such a wideband response can be obtained if the effective "Q" of the quartz crystal is kept low; this may be accomplished by keeping the power factor of the crystal less than unity or by adding a shunt resistance to the crystal with the power factor adjusted to unity. This will be discussed further in Chapter III.

Let us assume a [illegible] shape of a cube, [illegible] Let us further [illegible] this sample is [illegible] the extreme, [illegible] sample. For [illegible] Therefore, [illegible] be employed in [illegible] maximum or minimum.

This thesis [illegible] a power ratio [illegible] power to the [illegible] later in [illegible] in the piezoelectric [illegible] This transmitter [illegible] to be detected.

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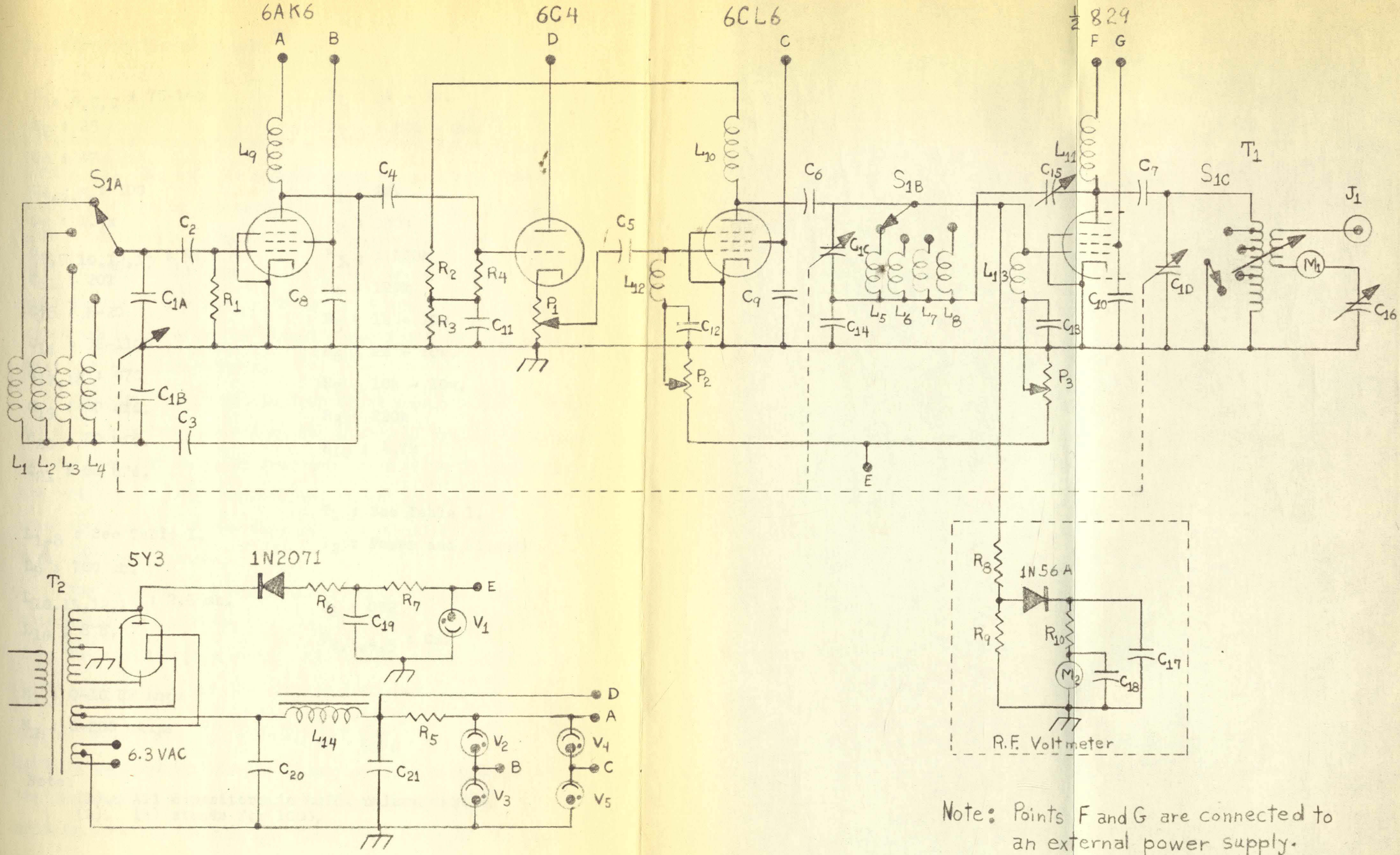
CHAPTER II

THE DESIGN OF THE EQUIPMENT

A. General Description

The radio frequency oscillator is designed to operate in the range of frequency from 4½ to 32 megacycles. It consists of four stages: (1) a Colpitts oscillator which is designed to operate in the range of frequency from 1½ to 15½ megacycles, (2) a cathode follower stage, (3) an amplifier-driver stage, and (4) a power amplifier which triples the oscillator frequency over the first two bands and doubles the frequency over the second two bands. This stage supplies power to the transmitting piezoelement.

It is possible to operate the power tube as a radio frequency oscillator; however, any variation in the plate supply voltage or any change in load impedance can cause a corresponding change in frequency. For this reason, the oscillator is isolated from the power stages by a cathode follower which draws no power from the oscillator. As an additional means of stabilizing the oscillator, the plate and screen grid supplies for the oscillator are regulated by means of gas tubes. As a result of these precautions the system is frequency stable under varying load conditions. (See Figure 1).



Note: Points F and G are connected to an external power supply.

FIGURE 1.

Circuit Diagram for Radio Frequency Power Oscillator

$C_{1A,B,C,D}$: 75-140

C_2 : 25

C_3 : 47

$C_{4,5,6}$: 100

C_7 : 1.5k

$C_{8,9,10,12,13}$: 5k

C_{11} : 20k

C_{15} : 5-20

C_{16} : 39-1100

$C_{17,18}$: 470

C_{19} : 40 ufd.

C_{20} : 80 ufd.

C_{21} : 60 ufd.

L_{1-8} : See Table I.

L_9 : 700 uh.

$L_{10,11,12,13}$: 2.5 mh.

L_{14} : 8 h.

M_1 : 0-10 RF Amps

M_2 : 0-200 uAmps

P_1 : 5k - 4w.

$P_{2,3}$: 50k - 2w.

R_1 : 22k

R_2 : 330k

$R_{3,9}$: 100k

R_4 : 120k

R_5 : 1k - 10w.

R_6 : 2k - 10w.

R_7 : 10k - 10w.

R_8 : 220k

R_{10} : 4.7k

T_1 : See Table I.

T_2 : Power and Filament

V_1 : OB2

$V_{2,3,4,5}$: OA2

Note:

(1). All capacitors in uufd. unless marked.
(2). (k) stands for 1000.

B. The Oscillator Stage:

The oscillator stage is a simple Colpitts circuit which is designed to operate in four bands. Selection of a band is accomplished by a band switch which changes inductors. The tube is a 6AK6 power pentode amplifier. The ganged tuning capacitors are variable from 25 to 110 uufd. Each section has a trimmer capacitor which can be used to extend the range by 40 uufd. In addition, the circuit has approximately 30 uufd. of stray capacitance which tends to lower the actual upper limit of each band from the calculated limit.

The available crystals operate at multiples of 5 megacycles; therefore, to reduce the number of bands, continuous tuning over the range of frequency from 4½ to 31 megacycles has not been rigidly adhered to. There is, however, an overlap of at least one megacycle above and below each multiple of 5 megacycles.

The frequency at which the circuit operates can be determined by examining the loop equations which are obtained from the equivalent circuit. The simultaneous solution of these equations gives the angular frequency

$$\omega = \sqrt{\frac{1}{L}\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{R}{r_p C_2}\right)}$$

In this equation (R) is the direct current resistance of the inductor in ohms, (L) is the self inductance of the coil in henries, (r_p) is the plate resistance of the 6AK6

tube in ohms, and (C_1 and C_2) are the tuning capacitances in farads. For the usual case one lets ($C_1 = C_2 = C$) and notes that ($r_p \gg R$); under these conditions the equation becomes approximately

$$\omega \cong \sqrt{\frac{2}{LC}}$$

One can calculate the inductance from this equation which will be resonant with the tuning capacitance at the required frequencies. (See Table I).

C. The Cathode Follower:

A 6C4 cathode follower after the oscillator stage serves two purposes: (1) it isolates the oscillator stage from the amplifier-driver stage, and (2) it serves as a gain control for the amplifier-driver stage. Over the frequency range in which the cathode follower must operate, it is quite inefficient; however, it is adequate to serve the twofold purpose mentioned above. (See Figure 2).

D. The Amplifier-Driver Stage:

At first it was thought that three, low-gain, resistance-capacitance coupled stages would provide sufficient power and peak voltage to drive a power amplifier through a range of frequencies from 5 to 25 megacycles. The voltage delivered was, however, found to be insufficient for class "C" operation of the power stage.

Later a single stage of amplification employing a 6CL6 power pentode amplifier was used to drive a power amplifier-tripler. This method was found to be unsatisfactory because the stage was unable to deliver sufficient tube in ohms, and C [illegible] in farads. For the normal [illegible] notes that ($r_p \gg$ [illegible] becomes approximately

$$q \approx \sqrt{\frac{[illegible]}{2C}}$$

One can calculate [illegible] will be received [illegible] frequencies. (See table [illegible]

C. The Oscillator [illegible]

A 6C4 triode [illegible] across the primaries [illegible] from the amplifier-[illegible] gain control for [illegible] frequency range [illegible] it is quite [illegible] the twelve [illegible]

D. The Amplifier [illegible]

At first it [illegible] amplitudes could [illegible] and peak voltage [illegible] range of frequencies [illegible] delivered [illegible] "Q" operation of [illegible]

Later [illegible] 6AQ5 power pentode [illegible] amplifier-driver [illegible] tory because the [illegible] power and peak voltage to drive a power amplifier through a range of frequencies from 5 to 25 megacycles. The voltage delivered was, however, found to be insufficient for class "C" operation of the power stage.

Later a single stage of amplification employing a 6CL6 power pentode amplifier was used to drive a power amplifier-tripler. This method was found to be unsatisfactory because the stage was unable to deliver sufficient peak voltage to drive the power amplifier-tripler over the desired bandwidth. The failure of the circuit to operate as expected was largely due to the fact that the transconductance of the 6CL6 tubes was well under the manufacturer's specifications.

Then the stage was redesigned to operate as a class "C" power amplifier. This method was found to be satisfactory after coils were wound so that the amplifier-driver would track the oscillator properly.

One final modification has been made in which the power amplifier stage is used to triple the first two bands. This required the rewinding of the plate circuit inductors for the second two bands of the amplifier-driver stage. The plate tuning circuit for the amplifier-driver stage is used as the grid tuning circuit for the power amplifier-frequency multiplier stage. This lowers the efficiency of both stages; a further disadvantage is a negative bias supply voltage which must be applied across the tuned

Table I. Characteristics of the Inductors for the Oscillator, the Power Amplifier-Driver, and the Power Amplifier-Frequency Multiplier

Band	Cap. uufd.	Freq. Mc.	KxFreq. Mc.	Ind.Osc. uh.	Ind.PA-D. uh.	Ind.PA-FM. uh.
1	140	1.40	4.20	185	92.5	10.4
1	75	1.90	5.70	185	92.5	10.4
2	140	2.90	8.70	43	21.5	2.4
2	75	3.96	11.9	43	21.5	2.4
3	140	6.00	12.0	10	5.00	1.26
3	75	8.23	16.5	10	5.00	1.26
4	140	12.0	24.0	2.5	1.25	0.32
4	75	16.4	32.8	2.5	1.25	0.32

(K) is (3) for bands 1 and 2. (K) is (2) for bands 3 and 4.

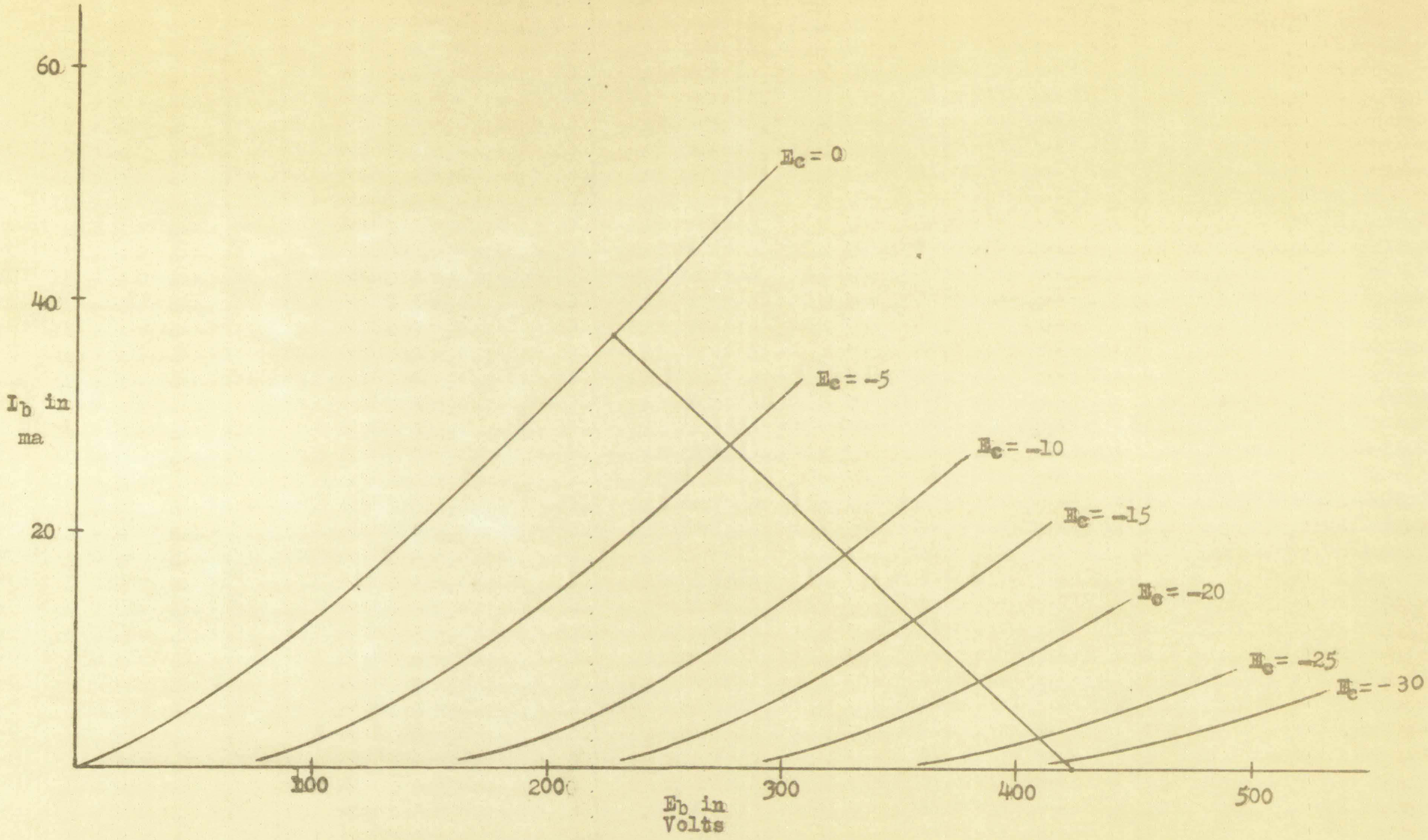


FIGURE 2.

Plate Characteristics for the 6C4 Triode With a Range of 220 Volts With E_{cc} Equal to 97 Volts.

circuit. These disadvantages are more than compensated for by the elimination of an additional tuned stage which would have to track the oscillator. (See Table II and Figure 3).

E. The Power Amplifier-Frequency Multiplier Stage:

In the power amplifier-frequency multiplier stage, the plate tuning circuit is tuned to the third harmonic for the first two bands and to the second harmonic for the second two bands. Harmonic in this case applies to the frequency of the signal which is applied to the grid of the tube. Effectively, to triple the fundamental frequency, the plate pulse must lie within a range of 80 to 120 electrical degrees; similarly, to double the fundamental frequency, the plate pulse must lie within a range of 90 to 120 electrical degrees. Operation of the circuit to obtain this optimum plate pulse angle can best be found by a trial and error method since the grid bias is a variable not encountered in the design of amplifiers whose operation is other than class "C". (See Table III and Figure 4).

A power amplifier whose plate circuit is tuned to the third harmonic is 40% efficient as compared to one which operates on the fundamental frequency; similarly, the efficiency for a frequency doubler is 55%. Therefore, it is necessary to design a power amplifier-frequency multiplier to deliver more power than a power amplifier which would operate as a straight class "C" amplifier if

Table II. Design Characteristics for the 6C16 Power Amplifier-Driver Stage.

Tube 6CL6

E_{bb} 420 v. E_{cc} -12.5 v. E_{gm} 15 v. E_{g2} 150 v.

E_{bmin} 2.5 v. E_{cmax} 2.5 v. E_{om} 417.5 v. θ_b 152.4°

θ_c 92° I_{ba} 17.3 ma. I_{1m} 29.4 ma. I_g N/A

P_1 6.15 w. P_{in} 7.26 w. P_d 1.11 w. η 85%

R_o 14.2 kohm n 18 k 9

θ	0°	10°	20°	30°	40°	50°	60°	70°
cos θ	1.000	0.985	0.940	0.866	0.766	0.643	0.500	0.342
$E_{om}\cos\theta$	417.5	412	393	362	320	269	209	143
E_b	2.5	6	25	56	98	149	209	275
I_{ba} ma.	60	60	60	60	50	33	13	4
$I_{ba}\cos\theta$	60	59.2	56.4	52	38.3	21.2	6.5	1.3

$$I_{ba} = 1/n\left[I_b(0)/2 + \sum_k I_b(k\pi/n)\right]$$

$$I_{1m} = 2/n\left[I_b(0)/2 + \sum_k I_b(k\pi/n)\cos(k\pi/n)\right]$$

$$P_{in} = E_{bb}I_{ba}$$

$$P_1 = E_{om}I_{1m}/2$$

$$P_d = P_{in} - P_1$$

$$R_o = E_{om}/I_{1m}$$

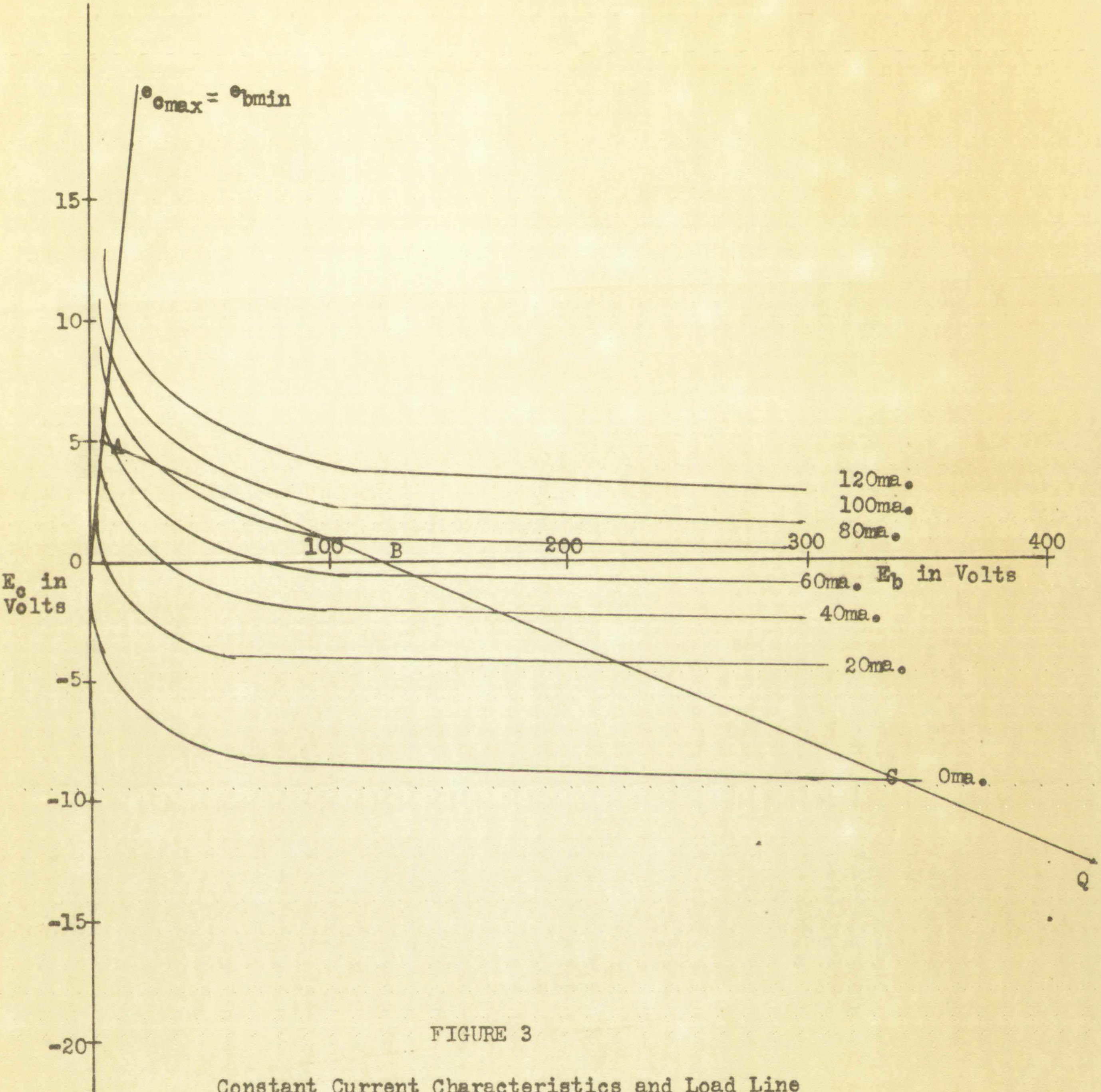


FIGURE 3

Constant Current Characteristics and Load Line

for the 6CL6 Power Amplifier-Driver Stage

one desires the same usable power (4).

The power amplifier is coupled to the external load by means of a transformer whose primary serves as the inductor of the plate tuning circuit. One side of the secondary is connected to ground through a variable tuning capacitor while the other side is connected to a type "N" connector at the front panel.

The coefficient of coupling of the transformer can be varied by changing the angle at which the plane of the secondary intersects the flux resulting from a current in the primary. The word "transformer" is somewhat loosely used here because of the high frequencies at which it operates. A better term would be "inductively coupled circuit."

Any change in the coefficient of coupling will cause a corresponding change in the mutual inductance of the transformer. The coefficient of coupling is related to the inductances in the following manner:

$$k = M/\sqrt{L_1L_2} \quad (5).$$

One attempt to measure the mutual inductance of the transformer by means of a low frequency bridge resulted in a value of 0.9 uh. This value would indicate a coefficient of coupling which is at least one order of magnitude higher than that normally attained by this type of transformer. This implies that the value for the mutual inductance is probably one order of magnitude too high.

Table III. Design Characteristics for the 829 Power Amplifier-Frequency Multiplier Stage.

Tube 829

E_{bb} 400 v.	E_{cc} -70 v.	E_{gm} 90 v.	E_{g2} 200 v.
E_{bmin} 20 v.	E_{cmax} 20 v.	E_{om} 380 v.	θ_b 114.6°
θ_c 78°	I_{ba} 112 ma.	I_{1m} 206 ma.	P_1 39.2 w.
P_{in} 44.8 w.	P_b 5.6 w.	η 87.5%	I_g 12.5 ma.
P_g 1.13 w.	R_o 1840 ohm	n 18	k 9

θ	0°	10°	20°	30°	40°	50°	60°
cos θ	1.000	0.985	0.940	0.866	0.766	0.643	0.500
$E_{om}\cos\theta$	380	374	357	329	291	245	190
E_b	20	26	43	71	109	155	210
I_{ba} ma.	600	560	510	375	225	45	0
$I_{ba}\cos\theta$	600	551	479	325	172	29	0
I_g ma.	100	90	65	10	0	0	0

$$I_{ba} = 1/n\left[I_b(0)/2 + \sum_k I_b(k\pi/n)\right]$$

$$I_{1m} = 2/n\left[I_b(0)/2 + \sum_k I_b(k\pi/n)\cos(k\pi/n)\right]$$

$$I_g = 1/n\left[I_g(0)/2 + \sum_k I_g(k\pi/n)\right]$$

$$P_{in} = E_{bb}I_{ba}$$

$$P_1 = E_{om}I_{1m}/2$$

$$P_d = P_{in} - P_1$$

$$P_g = E_{gm}I_g$$

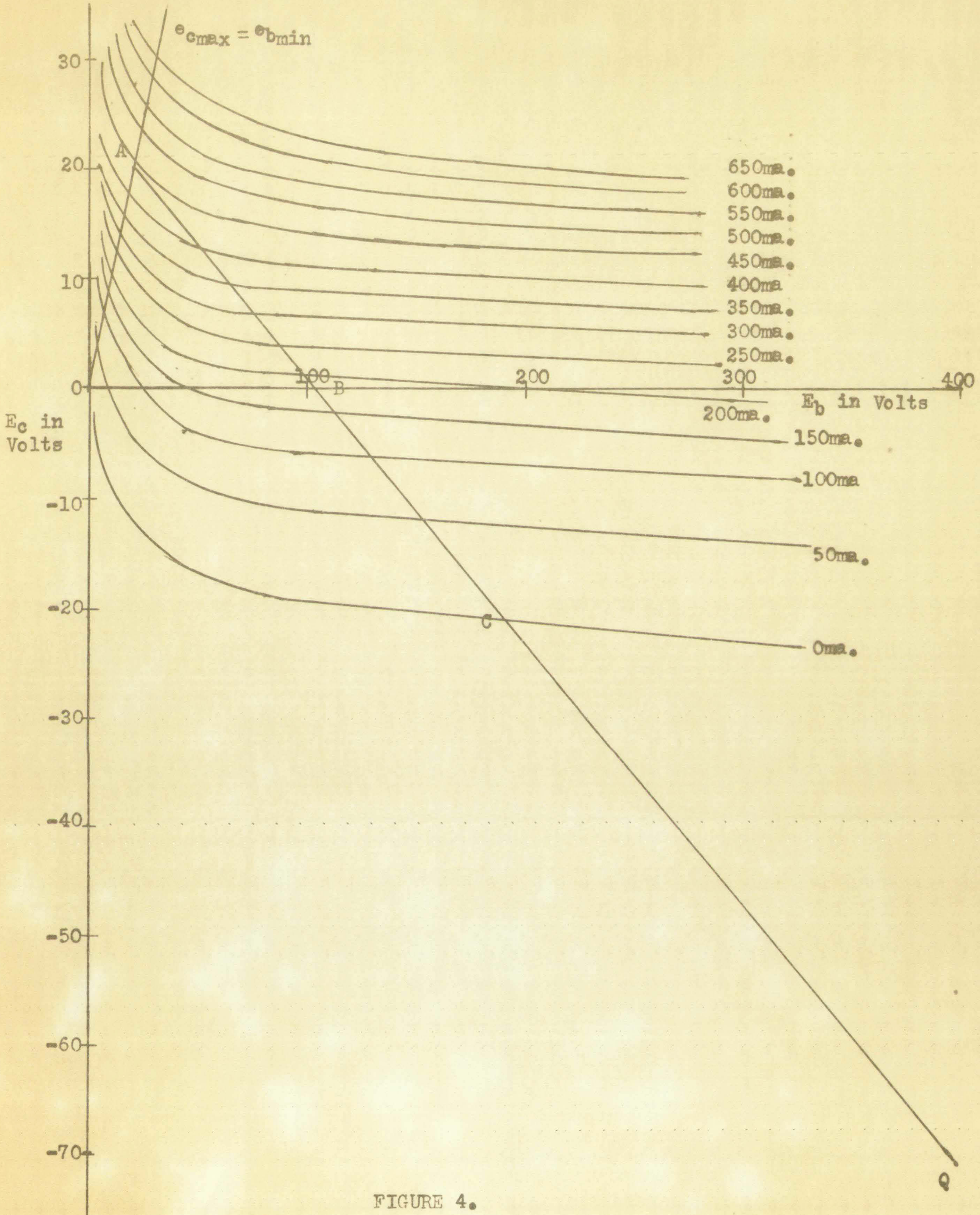


FIGURE 4.

Constant Current Characteristics and Load Line

for the 829 Power Amplifier-Frequency Multiplier

The shape of the secondary renders the calculation of the mutual inductance impractical.

The capability of varying the coefficient of coupling in this transformer is used as a means of regulating the power coupled to the piezoelement.

Because variation in the coupling and band switching require tapping the primary of the transformer for four different inductances, a calculation involving the mutual inductance and the coefficient of coupling has not been made. The output impedance has, however, been found experimentally (5). See Table IV).

Should more power be needed to excite the piezoelement, the power factor for the quartz crystal can be increased by properly tuning out the static capacitance of the crystal by means of an inductance inserted across the input to the crystal holder. This topic will be discussed further in Chapters III and IV.

Table IV. Output Impedance of the 829 Power Tube

Frequency Mc.	E_{oc} Volts	I_{sc} Ma.	Z_o Ohms
5	110	280	392
10	60	770	78
15	30	150	200
25	N/A	N/A	N/A
30	N/A	N/A	N/A

CHAPTER III

POWER TRANSFER TO THE PIEZOELEMENT:

Piezoelectric crystals have the property of being able to transform electrical energy into mechanical energy and mechanical energy into electrical energy. For the purpose of this experiment these correspond to the transmitting transducer and the receiving transducer, respectively. Since this thesis is particularly concerned with the ability to transfer power to the transmitting transducer from the oscillator, this discussion will be primarily concerned with the transmitting transducer.

Properly, to treat piezoelectric properties, it is necessary to use tensor notation since these properties are anisotropic, i.e., they depend on direction (6). However these piezoelectric properties can be treated by approximations which are adequate for the purpose of this experiment.

According to Hueter and Bolt (7) a piezoelectric sample which has electrodes attached to two opposite surfaces separated by length (L, meters) and of surface area (S, meters^2) will exhibit the properties of an electric capacitor with a capacitance

$$C_o = \epsilon \epsilon_o S/L \quad \text{Farads.}$$

The crystal also behaves like a mechanical spring with an internal stiffness constant that opposes an applied force. Since the oscillations are small, the system obeys Hook's law. The stiffness constant (c_{hk}, newtons/meter^2) is given by

$$c_{hk} = \frac{F/S}{\xi/L}.$$

It can also be written

$$c_{hk} = X_h/x_k$$

where (X_h) is (F/S), the stress, and (x_k) is (ξ/L), the strain. The subscript (hk) takes into account the anisotropy of the material.

If, while the crystal is compressed, the electrodes are short-circuited to equalize the potential across the sample, the polarization, or charge per unit cross-sectional area, is given by

$$P_i = e_{ik}x_k.$$

The subscripts (ik) indicate that any one of three pairs of opposite faces, (i), can be charged by any one of the six possible strains, (k); (e_{ik}) is the piezoelectric stress constant relating the strain (k) to a particular polarization vector (i).

If the face is firmly clamped so that it cannot change in length, the internal force developed per unit area is

$$X_h = e_{hj}E_j$$

where (E_j) is the field strength vector and (e_{hj}) is the piezoelectric stress constant relating a given field strength vector (j) to a particular stress component (h).

The relations

$$P_i = e_{ik} \cdot x_k \quad \text{and} \quad X_h = e_{hj} \cdot E_j$$

can be transposed into more useful forms which apply to receiving and transmitting transducers, respectively. The following relationships are necessary (7):

CURRENT: $i = S \cdot dP/dt$ amperes

POTENTIAL: $V = LE$ volts

VELOCITY: $u = d\xi/dt$ meters/second

FORCE: $F = SX$ newtons

In this more practical form the equations for transmitting and receiving piezoelectric transducers become (7):

TRANSMITTING: $F = S/L \cdot e_{hj} \cdot V = \alpha_{hj} \cdot V$

RECEIVING: $i = S/L \cdot e_{ik} \cdot u = \alpha_{ik} \cdot u$

These are the equations which are used in the design of piezoelectric transducer crystals; their primary purpose here is to define the (α's), which are transform quantities between electrical and mechanical energy.

The problem of transfering power from the oscillator to the piezoelement is simplified if one treats the transducer by means of an equivalent circuit. If the transducer is assumed to be clamped so that it radiates only from one side, it can be treated as a four terminal network (7). (See Figure 5).

where (d_{ij}) is the piezoelectric strain matrix and (e_{ij}) is the piezoelectric stress constant relating a given field strength vector (i) to a particular stress component (k).

The relations

$$S_j = d_{ij}E_i \quad \text{and} \quad T_j = e_{ij}E_i$$

can be rearranged into more useful forms with regard to receiving and transmitting transducers, respectively. The following relationships are necessary (6):

CURRENT: $i = dQ/dt$ amperes

VOLTAGE: $v = E\ell$ volts

VELOCITY: $u = \partial\xi/\partial t$ centimeters/second

FORCE: $F = ST$ newtons

In this more practical form the equations for transmitting and receiving piezoelectric transducers become (6):

TRANSMITTING: $F = eA/\ell \cdot v = \alpha_{ij} \cdot v$

RECEIVING: $i = eA/\ell \cdot u = \alpha_{ij} \cdot u$

These are the equations which are used in the design of piezoelectric transducers; their primary purpose here is to determine α_{ij}, which are transduction ratios between electrical and mechanical systems.

The analysis of transducer performance of a transducer using the piezoelectric is simplified by analyzing the transducer by means of an equivalent circuit. The transducer is assumed to be clamped so that it radiates only from one side, as may be expected of a two-port network (7). (See figure 7).

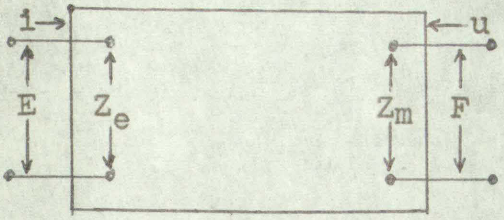


FIGURE 5

Equivalent Circuit of the Transmitting Crystal

At the output terminals a mechanical force (F) is applied over the surface (S) producing a particle motion velocity (u). If the motion is assumed to be of the plane wave type, the radiation resistance (Z_R), is given by

$$Z_R = \rho_0 cS,$$

which is equivalent to

$$Z_R = pS/u,$$

where the density of the medium into which the transducer radiates is (ρ_0) and (c) is the velocity of ultrasound in that medium.

If the transducer is tuned to resonance, the reactive elements of the network cancel. This leaves only a resistive term shunted by the static capacitance of the crystal.

The voltage applied to the input terminal of the transducer is time-varying; therefore, it produces a displacement current through the static capacitance of the crystal. This means that even if the crystal is operated at its resonant frequency, the power factor will be less than unity.

The power factor for the piezoelement at resonance is given by

$$\Phi = (1+\omega^2 C_o^2 R_e^2)^{-\frac{1}{2}}$$

where (C_o) is the static capacitance of the crystal, (R_e) is the effective resistance of the crystal, and (ω) is the angular frequency of the crystal at resonance. The power factor determines how much of the power available to the transducer can actually be used. The power factor can be made to approach unity if the static capacitance is tuned out by means of an inductor either in parallel or in series with the crystal. The power factor has been calculated for 5 and 10 megacycle crystals operating into various mediums. The inductances needed to cancel the static capacitance at the fundamental frequency and the available harmonics are listed in Table V.

In the present study we have used both 5 and 10 megacycle X-cut quartz crystals. These crystals when excited, produce longitudinal, compressional waves in a sample. These crystals will also operate at an odd harmonic, so that, for example, the 5 megacycle crystal can be used also at 15 and 25 megacycles.

The impedance presented to the oscillator by the crystal at resonance varies with the material which backs the crystal and with the material into which the crystal radiates. The material which backs the crystal in this experiment is brass. Compared to the wax-like substances

into which the crystal radiates, this presents a rigid backing. The crystal can then be treated as if it were rigidly clamped. This assumption, although not exactly true, is adequate for the purposes of this experiment. The resistance (R_e) is given by

$$R_e = \rho_o c S/\alpha^2 ,$$

where (α) is the transform factor between mechanical and electrical quantities discussed earlier in this chapter. Hueter and Bolt define it as

$$\alpha = e_{hj} . S/L ,$$

where (S) is the total radiating surface, (L) is the thickness of the crystal, and (e_{hj}) is the piezoelectric stress constant (7). Values for R_e are listed in Table IV. The calculated resistance which the crystal will present to the oscillator at different frequencies and with the crystal radiating into various materials are shown in Table VI.

The power factors of the 5 and 10 megacycle crystals operated at their fundamental frequencies and odd harmonics up to and including 30 megacycles are listed in Table VII.

Table VI. Equivalent Resistance for the 5 and 10 Megacycle Quartz Crystals Operating into Various Mediums.

Material	M kg/m^3	c m/sec	cS kg/sec	R_e (5Mc)	R_e(10Mc)
Quartz	2.65×10^3	5.50×10^3	4.14×10^3	5.98×10^5	1.49×10^5
Brass	8.44×10^3	3.50×10^3	8.39×10^3	1.21×10^6	3.03×10^5
Steel	7.83×10^3	4.90×10^3	1.09×10^4	1.57×10^6	3.93×10^5
Aluminum	2.70×10^3	5.10×10^3	3.91×10^3	5.66×10^5	1.42×10^5
Camphene	0.96×10^3	1.40×10^3	3.80×10^2	5.48×10^4	1.37×10^4
Camphor	0.99×10^3	1.40×10^3	3.94×10^2	5.68×10^4	1.42×10^4
Beeswax	0.96×10^3	0.90×10^3	2.44×10^2	3.52×10^4	8.81×10^3
Butter	0.86×10^3	0.80×10^3	1.96×10^2	2.83×10^4	7.08×10^3

$R_e = \rho_o cS/\alpha^2$

$\alpha^2 = (c_{11}S/L)^2$

Table VII. Power Factors for the 5 and 10 Megacycle Crystals Operating into Various Mediums. The Power Factor is Shown for the First Three Odd Harmonics and the First Two Odd Harmonics of the 5 and 10 Megacycle Crystals, Respectively.

Material	5Mc.	15Mc.	25Mc.	10Mc.	30Mc.
Quartz	0.0028	0.0010	0.0006	0.0028	0.0009
Brass	0.0014	0.0005	0.0004	0.0014	0.0005
Steel	0.0011	0.0004	0.0002	0.0011	0.0004
Aluminum	0.0029	0.0010	0.0006	0.0029	0.0010
Camphene	0.0311	0.0100	0.0061	0.0300	0.0100
Camphor	0.0291	0.0097	0.0058	0.0289	0.0097
Beeswax	0.0466	0.0156	0.0089	0.0472	0.0156
Butter	0.0586	0.0195	0.0117	0.0582	0.0194

Table VII. Power Factors for the 5 and 10 Megacycle Crystals Operating into Various Mediums. The Power Factor is Shown for the First Three Odd Harmonics and the First Two Odd Harmonics of the 5 and 10 Megacycle Crystals, Respectively.

Material	5Mc.	15Mc.	25Mc.	10Mc.	30Mc.
Quartz	0.0022	0.0010	[illegible]	[illegible]	[illegible]
Brass	0.0014	0.0005	0.0594	[illegible]	0.0005
Steel	0.0012	0.0004	[illegible]	[illegible]	[illegible]
Aluminum	0.0025	[illegible]	[illegible]	[illegible]	[illegible]
Camphene	0.0313	[illegible]	[illegible]	[illegible]	[illegible]
Camphor	0.0291	[illegible]	[illegible]	[illegible]	[illegible]
Beeswax	0.0455	[illegible]	[illegible]	[illegible]	[illegible]
Butter	0.0356	[illegible]	[illegible]	[illegible]	[illegible]

CHAPTER IV

DISCUSSION AND CONCLUSIONS

Previous work by this group on the velocity of ultrasound in camphene has shown that maxima are spaced on the order of tens of kilocycles; therefore, for ultrasonic waves of a few megacycles, it is imperative that the oscillator have very little frequency drift. This has been accomplished by the use of regulated power supplies for the oscillator and by isolation of the oscillator stage from the power amplifier stages by means of a cathode follower stage.

The output impedance of the power tube cannot be exactly matched to the impedance of the crystal. The crystal impedance at resonance is a function of the material into which the crystal radiates. When the crystal is radiating into a wax-like material such as camphene, the impedance of the crystal is close to that of the oscillator; however, when the crystal is radiating into a substance such as steel, the impedance of the crystal is much higher and, as a consequence, power transfer becomes much more difficult. In addition, the output impedance of the power tube cannot be calculated exactly without knowledge of the mutual inductance of the out-put transformer.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Previous work in this field of the generation of ultrasound in solids has shown that crystals are excited in the order of tens of kilocycles frequency, for ultrasonic waves of a few megacycles, it is imperative that the oscillator have very stable frequency output. This has been accomplished by the use of separated power supplies for the oscillator and by isolation of the oscillator stage from the power amplifier stage by means of a cathode follower stage.

The output impedance of the power tube cannot be exactly matched to the impedance of the crystal. The crystal impedance at resonance is a function of the material into which the crystal radiates. When the crystal is radiating into a low-loss material such as aluminum, the impedance of the crystal is close to that of the oscillator; however, when the crystal is radiating into a substance such as steel, the impedance of the crystal is much higher and, as a consequence, power transfer becomes much more difficult. In addition, the output impedance of the power tube cannot be calculated exactly without knowledge of the actual impedance of the out-put transformer.

The amount of useful power which the crystal can receive is a function of its power factor. The power factor can be made to approach unity by tuning out the static capacitance of the crystal by means of an inductor inserted in parallel with the crystal. However, calculations of the value of inductance required indicate that at frequencies above the fundamental the inductance is negligible. In fact the inherent inductance of the wiring may be sufficient to compensate or even overcompensate for the static capacitance. In the neighborhood of 5 megacycles it does become necessary to add an inductor in parallel with the crystal.

Any compensation which raises the power factor to unity will also raise the "Q" of the crystal; this will narrow the band of frequencies to which the crystal will respond. In this case it may thus become necessary to add resistance in parallel with the crystal to lower its "Q" so as to obtain sufficient band-width.

The pulse method has not been used because the oscillator cannot be gated rapidly enough to obtain a pulse of radio frequency with a rise time of only a few cycles. This might be accomplished by gating the power amplifier-frequency multiplier tube. Any attempt to gate the oscillator stage will result in a loss of frequency stability.

I would like to thank Professor John R. Green for giving me this interesting project for a thesis.

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A RADIO FREQUENCY POWER OSCILLATOR AND IMPEDANCE MATCHING DEVICE

By

Charles D. Preston

An Abstract of a Thesis
Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Physics

The University of New Mexico
1963

AN ABSTRACT OF THE THESIS

The interferometric method is used to obtain the velocity of ultrasound in a sample. This method requires the introduction of a high frequency mechanical vibration into the sample. This vibration transverses the sample, is detected, and brought into interference with a portion of the incident signal, or with its own echoes. In either case, maxima and minima occur as the phase difference passes through multiples of 2 , as the frequency is continuously varied. Therefore, it is necessary to have an oscillator capable of supplying sufficient power to excite the transmitting transducer, while at the same time, maintaining frequency stability. The design and operation of such an oscillator is the primary objective of this thesis.

The radio frequency oscillator consists of four stages: (1) a simple Colpitts oscillator, (2) a cathode follower for isolation purposes, (3) an amplifier-driver, and (4) a power amplifier-frequency multiplier, for which the transmitting transducer acts as a load.

The transmitting transducer presents a load which is frequency dependent, and which is dependent upon the density of the material into which the crystal is radiating, the velocity of ultrasound in that material, and the area of the transmitting transducer which is in operation.

If the crystal is operated at resonance, the radiation impedance reduces to a resistive term; the value of this term has been calculated, within the accuracy of the knowledge of the value of ultrasonic velocities in the material and of the material density, for the transmitting transducer operating into various materials. The results indicate that substances which are fairly rigid in structure present a higher value of resistance than the more wax-like substances such as camphene. One other hindrance to the transfer of power to the transmitting transducer is the static capacitance of the crystal. This can effectively be tuned out by means of an inductor placed in parallel with the static capacitance of the crystal to form a resonant load at the operating frequency of the crystal. If this is not done, the power factor of the crystal may fall well below unity.

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