THE INSTABILITY OF CIRCUITS EMPLOYING

SHORT RADIO WAVES

by

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INTRODUCTION

The use of very short radio waves as a means of communication is becoming more extensive every day. With their increased use has also come the problem of their extreme instability, a problem which was not experienced in the use of longer wave lengths. There are various factors both within and without an oscillator which determine its stability of operation. In this research, it was planned to study some of the factors which determine the frequency stability of high frequency self-excited oscillators.

DISCUSSION

It has been found in working with extremely short radio waves that even the most minute changes in any of the circuit constants cause a self-excited oscillation to change its fundamental frequency. The changes of the constants may even be so effective as to cause the oscillator to stop oscillating.

In order that the necessity for frequency stability may be better seen, let it be assumed that the range of audibility of the ear is 20,000 cycles per second. In the band of frequencies worked with in this problem, namely 15,000 kilocycles, a 0.5 per cent charge in frequency would change the fundamental frequency over a range of 75 kilocycles, or through a range of frequencies approximately four times the audibility range of the ear. From this, it is seen that for reliable communication, using a frequency of 15,000 kilocycles, the frequency must not vary from the fundamental over .125 per cent.

The Hartley oscillator used in this research has two capacitances in parallel which determine the frequency of oscillation of the circuit. There is the variable tuning capacitance which can be set at any desired point and is not subject to very great variations in capacity. The second capacitance, which shunts the tuning condenser, is the input capacity of the tube. The input capacity of the tube is the capacity between the grid and plate, grid and filament, and filament and plate. These various capacities, besides depending on the sizes and separations of the filament, grid and plate, are functions of the voltage amplification and effective resistance characteristics of the tube. The factors which determine the amplification and resistance characteristics are the filament current, grid voltage, and plate voltage. A change in any one of these is immediately followed by a change in the frequency of the radiated wave of the oscillator.

Heating of the apparatus, and vibration of the connecting wires also play a part in the instability of frequency. The amount of change due to thermal effects will depend on the coefficient of expansion of the various parts. The various parts of an oscillator are usually constructed of very substantial material so that vibration would have little effect on their constants. The main effects of vibration would come in the changes due to vibration of the connecting wires of the apparatus.

It was planned to study some of the above named factors by the audio-modulation of the frequency of a self-excited oscillator of 15,000 kilocycles frequency. In close proximity to this modulated oscillator, another high frequency oscillator of 16,000 kilocycles frequency is to be placed. Then, by an inductive or capacitive coupling, this resultant modulated beat is to be used to excite the grid of a 1000 kilocycle oscillator. Frequency modulation of the high frequency oscillator first, and then using this resulting beat, should produce much greater changes of the modulated frequency above and below the fundamental frequency of the 1000 kilocycle oscillator; whereas, if this 1000 kilocycle oscillator was frequency modulated directly, the change above and below its fundamental frequency would be very small, due to the small variations of the transmitter capacity. The above method should offer ample means of studying the effects of shielding, coupling of high frequency circuits, and the various factors which make an oscillator unstable.

THEORY

Electrostatic Shielding

From the start it was apparent that one of the greatest difficulties to be met in this problem was to eliminate the effects due to electromagnetic and electrostatic disturbances. The electromagnetic disturbances were due mainly to the magnetic coupling between the two oscillators. The electrostatic disturbances were due mainly to body capacities and other outside electric fields.

The theory of electrostatic shielding can best be shown by an analogy to Faraday's ice pail experiment. An electrostatic field exists wherever there is a potential difference such as the potential difference between two oppositely charged bodies. For perfect electrostatic shielding this difference of potential must be made zero.

We will assume that we have an oscillatory circuit completely shielded by a conducting metal box. Then if a positively charged body A (Plate I, Fig. 1) is brought close to the shield B, positive and negative charges will be induced on the shield. The negative charges will be attracted by the positively charged body A, while the positive charges induced on B will be repelled. The sum of the induced charges on B will at any one instant be zero. Thus there is

PLATE I

Fig 1

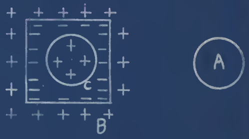

Fig. 2

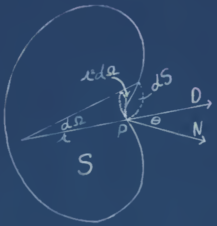

Fig. 3

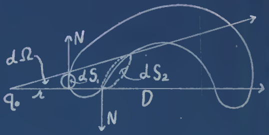

Fig. 4

no potential difference between the apparatus at C and the shield B.

If the shield had been placed around the apparatus C to shield an outside point A from the electrostatic effects of the apparatus C, the induced charges arrange themselves differently. Assuming that the apparatus C (Plate I, Fig.2) is positively charged, then a negative charge is attracted to the inner walls of the shield and an equal positive charge is induced on the outside of the shield, as is shown by Faraday's ice pail experiment. With a positive charge on C and a positive charge on the outside of the shield B, the effect is the same as if there were no shield around C. But let the outside of the shield be grounded so as to allow the positive induced charge to escape, then the point C will be perfectly shielded from A.

It was stated above that the potential of the shield was zero, a proof of which will now be made as given by Pierce in his book, "Electric Oscillations and Electric Waves", page 350.

Let us suppose that we have throughout a certain homogeneous dielectric of dielectric constant e and that there is an intrinsic charge q of electricity concentrated at a point within the region, and let us draw within the homogeneous region any closed surface S completely enclosing the charge q as is shown in (Plate I, Fig. 3).

At any point P on the surface, the electric induction is in the direction of r and has the magnitude

$$D = \frac{q}{r^2} \qquad (1)$$

where D is the electric induction.

The total flux induction outward through the closed surface is,

$$\phi_d = \int D \, dS \cos\theta \qquad (2)$$

Where θ is the angle between D and N and ϕ is the total flux induction outward through the closed surface.

Now if $d\Omega$ is the solid angle subtended at q by dS, it is seen by the geometry of the figure that

$$dS \cos\theta = r^2 d\Omega \qquad (3)$$

Then by substituting equations (1) and (3) in equation (2) we have,

$$\phi_o = q \int d\Omega = 4\pi q$$

It thus appears that in a homogeneous medium the flux of induction outward through any closed surface is independent of the position of q within the enclosure. The limitation that q must be concentrated at a point may hence be removed, and the charge q may be distributed in any manner whatever within the enclosure.

If on the other hand, we have a charge q within the homogeneous medium but outside of the enclosure, as shown (Plate I, Fig. 4), and if we draw a solid angle $d\Omega$ of q_0 intercepting from the closed surface elements dS_1 and dS_2 etc., it will be seen that at every element dS where the direction of r is into the enclosure cos (rN) is negative. Therefore,

$$\frac{dS_1 \cos (DN)}{r^2} = - d\Omega$$

and at every element dS_2 at which r points out from the enclosure cos (rN) is positive. Therefore,

$$\frac{dS_2 \cos (DN)}{r^2} = + d\Omega$$

and there are as many positive elements as negative elements hence the flux induction outward through all the elements intercepted by $d\Omega$ is zero. Therefore, the total flux of induction through a closed surface due to a charge outside of the enclosure is zero. From this we see that the potential difference of a shield would at every point be zero since the number of lines entering and leaving a shield, due to electrostatic induction would be equal,- i.e., when the potential difference is due to a charge outside of the shield. If the charge is inside of the shield the potential difference is made zero by allowing electrons to run up from the earth.

Electromagnetic Shielding

The shielding of a space against an electromagnetic wave presents a different problem. An electromagnetic wave has three components, (1) the velocity component which is in a direction out from the source, (2) the electric component which is in a vertical plane, (3) the magnetic component which is in the horizontal plane, all of which are mutually perpendicular.

The shielding of a space from electromagnetic waves depends on the frequency of these waves. When the frequency is very low, the electric and magnetic field change so slowly that the problem is nearly one of shielding a stationary field and can be accomplished by almost any conducting material. When the frequency is very high, the problem is one of the resistance of the magnetic materials.

If, when a shield is placed around an electromagnetic wave, all the energy of the radiated wave is dissipated in the metal conductor surrounding the apparatus, the shielding has only been accomplished in a theoretical way, thus in practice the ability of a magnetic material to cut off these electromagnetic waves is termed its shielding power. The shielding power of a conductor is defined as the ratio of the decrease in the amplitude of the wave when the shield is present to the amplitude of the wave when the shield is not present and is given by the formula;

$$S = \frac{A_o - A_s}{A_o}$$

where: S = the shielding power

A_o= Amplitude of wave when the shield is not present

A_s= Amplitude of wave when the shield is present.

The shielding of a circuit for electromagnetic disturbances is brought about by the eddy currents which the changing electromagnetic waves produce in the shield. As the current in the shield in turn radiates electromagnetic waves, we assume that the apparatus and shield are far enough apart that there is no reaction between the two circuits i.e., between the oscillator and shield.

If we take an oscillator in operation, there is an alternating current flowing in the inductance A, (Plate II, Fig. 5) which is given by,

$$I_1 = I_o \sin \omega t$$

At any one instant the lines of force from the changing alternating current field are moving in a certain direction. In this case we will assume the lines of force at the particular instant to be moving in the direction of the

PLATE II

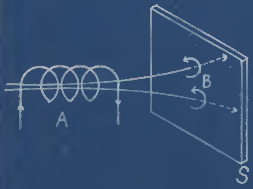

Fig 5

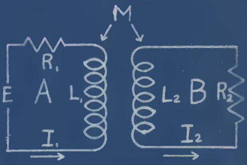

Fig. 6

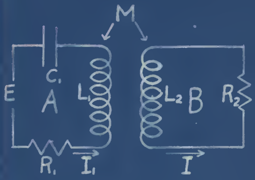

Fig 7

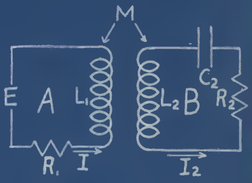

Fig. 8

shield S, as shown by the arrows. The shield being a conducting surface can be taken as consisting of an infinite number of small closed coils of wire. Then these changing lines of force from coil A will induce electromotive forces in these small coils. According to Lenz's Law, this changing current, with its changing flux linkages causes a counter electromotive force to flow in these small coils in a direction as shown by B in the diagram, such as to oppose any change by the inducing current, and is 180° out of phase with the inducing current.

The sum of the electromotive forces set up by this changing field and the RI-drop experienced by the eddy currents in the shield must be equal to zero and can be stated mathematically as follows:

$$L_2 \frac{dI_2}{dt} + M \frac{dI_1}{dt} + R_2 I_2 = 0 \quad (1)$$

where;

L_2 = the self inductance of the shield

I_2 = the reactive current set up in the shield

I_1 = the active current induced in the shield

M = the mutual inductance between the oscillator and shield

R_2 = resistance of the shield

For 100 per cent shielding, the resistance of R_2 must be negligible, then equation (1) reduces the form;

$$L_2 \frac{dI_2}{dt} + M \frac{dI_1}{dt} = 0 \qquad (2)$$

$$\text{or} \quad -L_2 \frac{dI_2}{dt} = + M \frac{dI_1}{dt} \qquad (3)$$

On integrating equation (2)

$$L_2 I_2 + M I_1 = \text{constant} \qquad (4)$$

$L_2 I_2$ is the magnetic flux through the closed circuit of the shield due to the current I_2 flowing in it, and $M I_1$ is the flux due to the current I_1, and since the sum of these two is constant, the variation in flux, which without the closed circuit would be

$$M_o I_1 \sin \omega t,$$

is reduced to zero.

From equation (3) we see that the inducing electromotive force $M \frac{dI_1}{dt}$ does produce an equal and opposite back electromotive force $L_2 \frac{dI_2}{dt}$ provided that the resistance of the shield is negligible. But in all shields or conductors the resistance is not negligible. Thus the changing electromotive force in the shield, due to its induced current and resistance, will radiate electromagnetic waves as from a wire, making the shielding less perfect the higher the resistance of the shield. The resistance of the shield has the same effect as adding resistance to the circuit and this resistance increases as the thickness of the shield is increased up to a certain maximum. After that, the resistance added to the circuit decreases.

Effects of Magnetic Coupling on a Neighboring Circuit

The two high frequency oscillators used in this research were built in such a way that there was a large magnetic coupling between the two, even after being shielded. To show the effect of resistance, capacity, and inductance of one circuit on another operating in close proximity, a portion of the mathematical theory of these effects will be taken from Morecroft's, "Principles of Radio Communication", page 105 and following.

To begin with, we will assume a current I, acting in one circuit and find the voltage E_2 induced in the second circuit. We will assume also that the circuit is only resistance and inductance, the capacitance reactance to be taken up later. The voltage E, acting in circuit A (Plate II, Fig. 6) will produce current in the second circuit B, which current is divided into two components, active and reactive, in phase with E_2 and out of phase 90° with E_2. The active component of E_2 will be 90° behind the primary current and will produce an electromotive force in the primary circuit A that is 180° out of phase with the primary current.

If we assume that the current I flowing in the primary circuit is one ampere, this current will induce an electromotive force in the circuit B.

$$E_2 = \omega M I_1 = \omega M$$

where M is the mutual inductance

$$\omega = 2\pi f$$

The current in circuit B will be,

$$I_2 = \frac{E_2}{Z_2} = \frac{\omega M}{Z_2}$$

where Z_2 is the impedance of circuit B.
This current I_2 lags behind E_2 by an angle θ, the tangent of which $= \dfrac{\omega L2}{R_2} = \dfrac{\text{Inductive reactance}}{\text{Resistance}}$

The active component of I_2 is in phase with E_2 then,

$$I_2 \cos\theta = \frac{\omega M}{Z_2} \cdot \frac{R_2}{Z_2}$$

The electromotive force induced in circuit A by this current is, $I_2 \cos\theta . \omega M = \frac{\omega M}{Z_2} \cdot \frac{R_2 \omega M}{Z_2} = \left(\frac{\omega M}{Z_2}\right)^2 R_2$

As this voltage lags 90° behind the inducing current $I_2 \cos\theta$, and $I_2 \cos\theta$ lags 90° behind I_1, this voltage $\left(\frac{\omega M}{Z_2}\right)^2 R_2$ is 180° behind I_1, and so is an I R reaction. Since we assumed a unit current in circuit A, this voltage $\left(\frac{\omega M}{Z_2}\right)^2 R_2$ is an increase in the resistance of circuit A due to circuit B.

Hence the apparent resistance of R_1' of circuit A is,

$$R_1' = R_1 + \left(\frac{\omega M}{Z_2}\right)^2$$

The reactive current in circuit B is $I_2 \sin\theta$, and this current lags 90° behind E_2, which itself lags 90° behind I_1. The voltage induced in circuit A by this current $I_2 \sin\theta$ is equal to $M \sin\theta$, and this will be 90° behind the inducing current $I^2 \sin\theta$ and hence will be 270° behind I_1, or it leads I_1 by 90°.

The reactive voltage in circuit A due to L_1 is 90° behind I_1. This makes the current I_1 lead the reactive voltage by 90°, whereas an inductive circuit draws a lagging current but it must be remembered that the component of the impressed electromotive force which overcomes the reacting voltage of a circuit must be 180° ahead of the reacting voltage itself. This makes the current in an inductive circuit lag behind the impressed electromotive force as it should.

From this it appears that the voltage induced in circuit A by the current $I_2 \sin\theta$ is 180° out of phase with the reactive voltage in the circuit A due to the inductance L_1 of circuit A. Hence the total reactive voltage of circuit A will be less when circuit B is present than when it is not present.

The amount of electomotive force induced in circuit A by $I_2 \sin\theta$ is $\omega MI_2 \sin\theta$, and this is equal to

$$\left(\frac{\omega M}{Z_2}\right)^2 \omega L$$

Therefore, the total reactive voltage in circuit A when a current of one ampere is flowing is,

$$\omega L_1 - \left(\frac{\omega M}{Z_2}\right)^2 L_2 = \omega\left[L_1 - \left(\frac{\omega M}{Z_2}\right)^2 L_2\right]$$

and from this we get the equivalent self induction of circuit A,

$$L_1' = L_1 - \left(\frac{\omega M}{Z_2}\right)^2 L_2 ,$$

which is the difference between the total inductance and the mutual inductance.

It is therefore seen that the effect of the current in circuit B is to increase the resistance of circuit A by the amount $\left(\frac{\omega M}{Z_2}\right)^2 R_2$ and to decrease the self induction by an amount $\left(\frac{\omega M}{Z_2}\right)^2 L_2$.

If a condenser is added to the primary of circuit A, (Plate II, Fig. 7), the characteristics can be written from the above derivation,

$$R_1' = R_1 + \left(\frac{\omega M}{Z_2}\right)^2 R_2$$

$$L_1' = L_1 - \left(\frac{\omega M}{Z_2}\right)^2 L_2$$

Then $I_1 = \dfrac{E}{\sqrt{\left[R_1 + \left(\frac{\omega M}{Z_2}\right)^2 R^2\right]^2 + \left[\omega\left(L_1 - \left(\frac{\omega M}{Z_2}\right) L_2\right]^2}}$

$$E_2 = \frac{\omega M E}{Z_2}$$

$$I_2 = \frac{E_2}{Z_2} = \frac{E\omega M}{Z_2\sqrt{\left[R_1 + \left(\frac{\omega M}{Z_2}\right)^2\right]^2 + \left[\omega\left(L_1 - \left(\frac{\omega M}{Z_2}\right)^2 L_2 - \frac{1}{\omega C_1}\right]^2}}$$

In case the impressed frequency is adjusted to give resonance in the primary circuit A without the presence of the secondary, these equations reduce to the form;

$$I_1 = \frac{E\,Z_2}{\sqrt{\left(\omega^2 M^2 + R_1 R_2\right)^2 + \omega^2 L_2^2 R_1^2}}$$

$$I_2 = \frac{E\,\omega\,M}{\sqrt{\left(\omega^2 M^2 + R_1 R_2\right)^2 + \omega^2 L_2 R_1^2}}$$

If M is varied a maximum current will flow in the secondary when

$$\omega^2 M^2 = R_1\sqrt{R_2^2 + \left(\omega L_2\right)^2} = R_1 Z_2$$

For this value of M the value of the two currents become,

$$I_1 = \frac{E\,Z_2}{R_1\sqrt{2\left(Z_2^2 + R_2 Z_2\right)}}$$

$$I_2 = \frac{E\,\omega\,M}{R_1\sqrt{2\left(Z_2^2 + R_2 Z_2\right)}}$$

The current in I_1 will decrease as the impedence Z_2 is decreased or, - that is, as M the mutual induction between the two circuits becomes less. Then, as the mutual induction is made less, the current I_2 approaches zero and is zero when M is zero.

The circuit is now considered with the condenser in the secondary circuit B, as is shown in the diagram Plate II, Fig. 8.

In this circuit the resistance of the primary is always increased by the presence of the secondary, but the effect upon the inductance depends upon the frequency impressed upon the primary circuit. If the frequency is such as to satisfy the conditions for resonance in the secondary,

$$f = \frac{1}{2\pi\sqrt{L\,C}}$$

the apparent inductance of circuit A will be the same as the actual inductance; i.e, the presence of circuit B does not affect the inductance of circuit A.

With higher than resonant frequency the apparent inductance of circuit A is decreased by circuit B, and with lower frequency the inductance of circuit A is increased. In other words, if I_2 lags behind E_2, the effect on circuit A is to cause an increase in its apparent inductance.

The equations for the apparent resistance and self inductance would be,

$$R_1' = R_1 + \left(\frac{\omega M}{Z_2}\right)^2 R_2^2$$

$$L_1' = L_1 + \left(\frac{\omega M}{Z_2}\right)^2 L_2$$

From this it is seen that if $\frac{1}{\omega^2 C^2}$ is greater than L_2, L_1' is greater than L_1; if $L_2 = \frac{1}{\omega^2 C^2}$, $L_1' = L_1$; if L_2 is greater than $\frac{1}{\omega^2 C^2}$, then L_1' is less than L_1.

Another factor to be considered in stabilizing a self-excited oscillation is the effect due to the heating of the various parts of the apparatus and tube.

We will first take the inductance coil. From the formula for computing the approximate inductance of a coil,

$$L = \frac{4\pi^2 N^2 A^2 K}{L},$$

where A is the radius of the coil, it can be seen that the inductance of a coil varies directly as the square of the radius. Any expansion then would be to increase the value of the inductance. This increased inductance would then change the frequency to a lower value.

We next take into consideration the expansion of the tuning condenser. There are two effects in a condenser due to heating, first the effect due to the linear expansion of the shaft and stationary plate mountings; second the effect due to surface expansion of the plates. From the formula for the capacity of a condenser,

$$C = \frac{K A}{4\pi d} \quad \text{where } A = \text{area of plates}$$
$$d = \text{distance between the plates}$$

it is seen that the capacity of a condenser is directly proportional to the area of the plates and inversely proportional to the distance between the plates. Since the two factors increase and decrease at the same time, the resultant capacity of the condenser would be very nearly constant. The capacity of the condenser would vary from this constant.only when the relative change of area compared to the distance apart of the plates is large. From the above analogy, it would appear that increasing the temperature of the inductance coil and tuning condenser would cause the frequency to drift to a lower value.

Tube Changes

In the Hartley oscillating circuit as used in this experiment, the tuning condenser is shunted by the input capacity of the tube. This input capacity is a function of the plate load, grid to plate, and grid to filament capacities of the tube. This input capacity is given by the formula,

$$C_i = C_g\text{-}f + C_g\text{-}p \left(\frac{\mu R_o}{R_o + R_p} + 1 \right)$$

where,

C_i = Input capacity of the tube

C_g-f = Grid to filament capacity

C_g-p = Grid to plate capacity

μ = Amplification constant of tube

R_o = Load resistance

R_p = Alternating current plate resistance

Heating of the filament, grid and plate will produce changes in the plate resistance R_p of the tube, and any change in R_p in turn causes the voltage amplification $\frac{\mu R_o}{R_o + R_p}$ to fluctuate. Since the grid to plate capacity of the tube is a direct function of this amplification factor, any change in it would change the input capacity of the tube and in turn the fundamental frequency of the oscillator.

Variations in filament current, grid voltage and plate voltage also affect the voltage amplification of the tube. A slight increase or decrease in filament current I_f changes the average flow of electrons to the plate, this electron flow which constitutes the plate current is one of the determining factors of the resistance of the plate circuit Rp of the tube. Fluctuations in the plate voltage E_p also change the resistance of the plate circuit of the tube. The fluctuations of the plate voltage and filament current in turn affect the grid voltage E_g. Variation of these three factors change the mutual conductance and voltage amplification of the tube, which again changes its input capacity.

Mechanical Vibrations

The mechanical vibrations of the various parts of the apparatus and connecting wires are also a factor in determining the frequency stability of an oscillator. The distributed capacity of the connecting wires and wires of the inductance is also considered as part of the input capacity of a condenser, $C = \frac{KA}{4\pi d}$, we see that the capacity varies inversely as the distance between the plates. The wires of the inductance and connecting wires are considered as condenser plates and their distance of separation, the distance between the plates. If the wires are subject to jars of any kind, the wires will be set in vibration, the amplitude of this vibration depending upon the size of cross section of the wire and the distance apart of the supports of the wire. This distance apart of the supports of the wires also determines the frequency at which they will vibrate, the frequency being inversely proportional to the length of the vibration. This vibratory motion of the wires would make the distributed capacity of the circuit vibrate about a certain level, which in turn would affect the fundamental frequency of the oscillator, causing it to have a periodic fluctuation.

CONSTRUCTION OF APPARATUS

In the working out of this problem it was necessary to construct three separate oscillators, two oscillators in the range of 15,000 kilocycles frequency and one oscillator of 1000 kilocycles frequency.

The two high frequency oscillators were made first. Two National Girder Frame short wave tuning condensers were purchased. These condensers were then double spaced, i.e., the distance between the plates of the stator and rotor was doubled. Increasing the distance between the plates enhances the insulating qualities of the condenser for use in an oscillator where high voltages are used. Double spacing also increases the sensitivity of tuning by spreading the original band of the condenser over twice the original dial space.

The rated capacity of the condensers before alteration was 15-50 micromicrofarads. Since double spacing decreased the capacity by one-half, the capacity would then be 7.5-25 micromicrofarads. By using the formula for finding the frequency of oscillation of a circuit,

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where L = Inductance
C = Capacity
f = Frequency

or

$$LC = \frac{1}{4\pi^2 f^2} ,$$

it was calculated that the LC value must be .000113, the LC product being constant for any one frequency. Taking any value for the capacity between 7.5 and 25 micromicrofarads and dividing it into the LC product .000113 will give the value of the necessary inductance. If 20 micromicrofarads is taken as the capacity value at 15,000 kilocycles, the inductance must have a value of .565 microhenries.

The inductances used in with these condensers were made as nearly identical as possible. Number 4 Brown and Sharp copper wire was used for winding the coils. By making various substitutions of radius and length in Nagaoka's formula for the approximate inductance of a coil,

$$L = \frac{4\pi^2 n^2 R^2 K}{L} ,$$

where n = number of turns of wire

L = length of winding

R = radius of coil

K = a constant from 2R/L

it was found that the following dimensions,

R = 4 cm.

L = 6 cm.

n = 3 cm.

gave a calculated inductance of .574 microhenries. This being close enough to the desired inductance, two coild were wound of this size.

When this LC combination was placed in an oscillator circuit the frequency range was found to vary from approximately 13,000 to 16,000 kilocycles over the upper half of the condenser. When the condenser value was decreased below the half way point, the circuit would stop oscillating. For measuring this frequency, a General Radio short-wave meter was used, employing a zero beat method.*

Some preliminary work had shown that there was a large frequency drift due to capacity effects, caused by using a tube socket with a metal base. Consequently, a different type of tube socket had to be made, eliminating as much

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* A Precision Method for Measurement of High Frequency. C. B. Atkins, Proceedings of I.R.E., February 1928.

unnecessary metal as possible and still providing for good connections. The base was made of bakelite, one-half inch thick by two inches square. For holding the tube, four pieces one-fourth inch brass bar, one and one-fourth inches long were used. Holes were drilled for the tube prongs and for bolting the brass bars to the base of bakelite. The ends through which the tube protruded were split vertically and a set screw run through from the side to insure better contact between the brass bar and tube prong. A one inch hole was bored through the center of the base to provide better insulation against high frequency currents.

The by-pass condensers used in the high frequency oscillators were of .002 microfarad capacity. The two radio frequency choke coils used in the high frequency oscillators were wound on pieces of fibre tube, one and one-half inch by one inch diameter. The windings placed thereon were each one and one-fourth inches long and consisted of 32 turns of No. 24 single cotton covered wire. From the Nagaoka's formula the inductance was calculated and found to be 15 microhenries. An inductance of this size would then give a reactance of 707 ohms. (Reactance $X_L = 2\pi fL$).

The 1000 kilocycle oscillator was made from apparatus at hand in the laboratory. A slight amount of alteration was done to the variable condenser. It was originally a 33 plate receiving condenser, with a vernier adjustment. This vernier adjustment was removed and the plates double spaced. This increased width of the condenser by double spacing necessitated the turning out of a new shaft for the rotor.

The inductance coil used was an oscillation transformer that was formerly used in a spark transmitter. The inductance of this coil was calculated by Nagaoko's formula, $L = \frac{4\pi^2 n^2 R^2}{L} K$, from the following dimensions:

$$L = 19.05 \text{ cm.}$$

$$R = 8.25 \text{ cm.}$$

$$n = 25$$

$$\frac{2R}{L} = .865$$

$$K = .72$$

and was found to have an inductance of 63.5 microhenries.

When this LC combination was placed in an oscillating circuit, its wave length range was from 103.5 meters to 293 meters or a frequency range from 2400-1025 kilocycles. A Kolster wavemeter, accurate to .5 per cent, was used for the above measurements.

The variable condensers of the oscillators were mounted on a 13½ inch square by 5/16 inch thick bakelite panel. The frame work back of the panel for mounting the various other parts, was made in two levels. The two high frequency oscillators were placed on the bottom level, four inches apart. The tube base was placed as close to the LC circuit as practicable in order that the grid and plate leads might be made as short as possible.

On the upper level, the parts for the 1000 kilocycle oscillator were placed. The oscillation transformer was placed to the rear of this level. This gave room to place the tube socket in the area between the condenser and inductance.

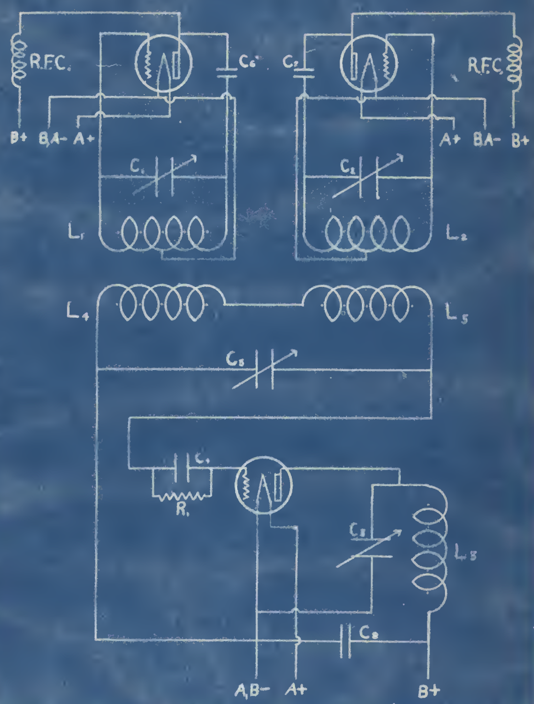
Also on the panel was mounted a Bradleystat grid leak for adjusting the bias on the grid of the 1000 kilocycle oscillator.

The various parts of the high frequency oscillators were electrically connected together by strips of copper. Number 12 copper wire was used for connecting wires of the 1000 kilocycle oscillator. Plate III shows a schematic diagram of the connections made in the oscillators, followed on the next page by a table of constants.

For shielding the high frequency oscillators, 1/64 inch sheet copper was used. The high frequency oscillators were completely enclosed in this copper shield. They were also shielded from one another by a sheet of copper.

A separate power supply was used for the filament and plate circuit of each oscillator. When U X 201A tubes were used in the high frequency oscillator circuit, their plate supply was furnished by two B-battery eliminators, made by

PLATE III



Schematic Diagram of Oscillators

TABLE OF CONSTANTS FOR OSCILLATOR

L_1 and L_2	3 turns, No. 4 copper wire, 8 centimeters in diameter.
L_3	Oscillation transformer
L_4 and L_5	25 turns, No. 26 cotton covered wire, 7 centimeters in diameter.
C_1 and C_2	50-micromicrofarads capacity, variable, double-spaced.
C_3	250-micromicrofarads capacity, variable tuning condenser.
C_4	250-micromicrofarad, grid condenser.
C_5	31-plate, double-spaced, variable condenser.
C_6 and C_7	.002-microfarad by-pass condensers.
R_1	Bradleystat adjustable grid leak.
R.F.C.	32 turns, No. 24 single cotton covered wire 1 inch in diameter.

the Kellogg Switchboard Company. The maximum no load voltage of these eliminators was 250 volts, any less voltage than this being controlled by a rheostat built in the eliminator box. The filament supply for the 201A tubes was furnished by a 6 volt lead storage battery, the current being controlled by a non-inductive, carbon pile rheostat.

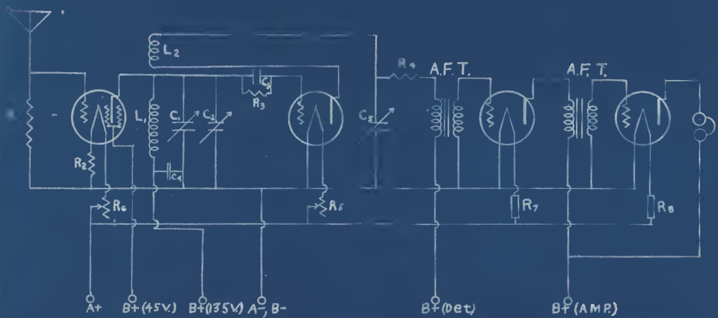
The oscillator tube for the 1000 kilocycle oscillator, was a Radiotron UX-865 screen grid tube, rated at;

E_b = 500 volts	E_d = 125 volts
E_c = 0	I_f = 2 amperes
I_p = 21 milliamperes	E_f = 7.5 volts

For a plate current of 500 volts, eleven 45 volt B batteries were available. The filament current supply was taken from either of two sources, an Edison storage battery of 9 volts or a step-down alternating current transformer. Filament current adjustments were made by a non-inductive carbon-pile rheostat.

The receiver used for detecting the radiated wave of the oscillators was also home-made, being built around a set of short-wave plug-in coils that had been purchased. A three plate tuning condenser was used for coarse adjustment, and shunting this, there was placed a two plate trimmer condenser for critical adjustment. Plate IV gives a schematic diagram of the connection used in the receiver,

PLATE IV



Schematic Diagram of Short-Wave Receiver

TABLE OF CONSTANTS FOR RECEIVER

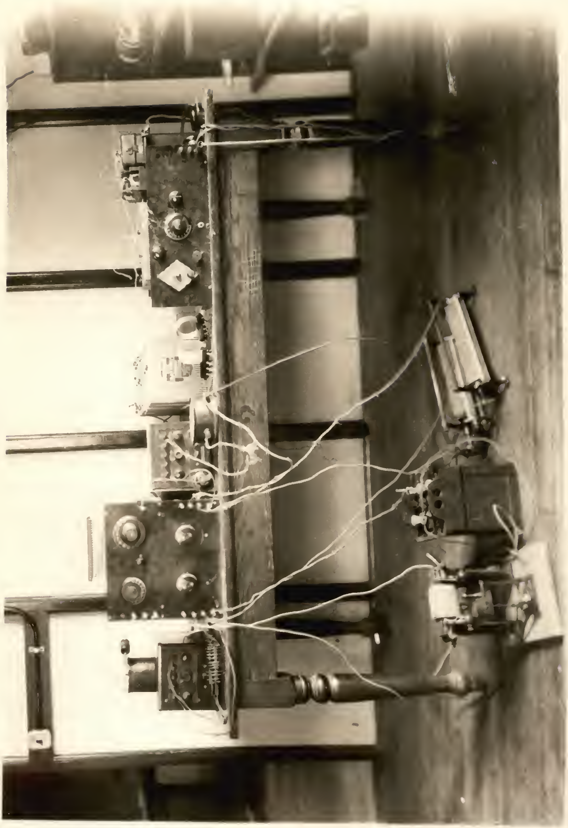
L_1	3 turns, No. 18 single cotton covered wire, spaced 10 turns to the inch.
L_2	6 turns, No. 18 single cotton covered wire, spaced 10 turns to the inch.
C_1	3-plate variable tuning condenser.
C_2	2-plate trimmer condenser.
C_3	.00025-microfarad grid condenser.
C_4	.006-microfarad by-pass condenser.
C_5	.00025-microfarad variable condenser.
R_1	100,000-ohm fixed resistance.
R_2	15-ohm fixed resistance.
R_3	5-megohm grid-leak resistance.
R_4	25,000-ohm fixed resistance.
R_5 and R_6	20-ohm variable rheostats.
R_7 and R_8	.25-ampere Amperites.

followed by a table of constants on the next page. This hook-up is the conventional regenerative receiver plus one stage of untuned radio frequency amplification used as a blocking tube to keep oscillations from the detector circuit being radiated in the antenna circuit. The receiver was entirely shielded by 1/64 inch copper plate. The plate was used as a return wire for all ground connections.

Plate V is a photograph of all the apparatus used in this research. On the right end of the table is the short-wave receiver with two of the short-wave plug-in coils lying to the left of it. On the other end of the table are the oscillators. On either side of the oscillators are the Kellogg B-battery eliminators. Resting on top of the left eliminator is the General Radio short-wave wavemeter. In front of the other B-eliminator is the plate current milliammeter. Resting on the floor are the alternating current step-down transformer, six volt storage battery, and the two non-inductive carbon pile rheostats.

In an effort to get a 1000-kilocycle beat that would excite the grid of the low frequency oscillator, various sizes of inductance coils were used. When a method of resonating this 1000-kilocycle beat was used, the coupling coils were wound on a three inch diameter insulating cardboard tube. The tube was eight inches long. A coil of 25

PLATE V



turns of wire was placed one-half inch from each end, and these were connected so that they were in a series aiding connection. These coils were then connected in series with a 23 plate tuning condenser, as shown in the diagram of the oscillators. (See Plate III).

When the coupling between the oscillators was by means of an aperiodic link, two coils two inches in diameter and four and one-half inches long were wound of magnet wire. The coils were first wound on an iron tube. The iron tube was then removed and the coil made to retain its shape by two thin bakelite strips bolted to it. These coils are shown in the plate lying in front of the extreme left B-eliminator.

RESULTS AND CONCLUSIONS

The results of this research showed that the shielding of a receiver or transmitter added much to the stability of the received or transmitted wave. The effects of extraneous capacity was most noted in working with the receiver. When an unshielded receiver was tuned to an incoming wave of 15,000 kilocycles, a slight movement of anyone in the room would cause the capacity of the set to vary so much that the incoming wave was tuned out entirely. When the operator tuned the receiver to an incoming wave while standing close to the receiver, and then moved away from the receiver four feet and the receiver was retuned to the incoming wave, it was found that the effect of body capacity on the tuning of the receiver was to change the frequency from 5000 to 7000 kilocycles. The condenser dial had previously been calibrated to read kilocycles.

It was the experiments just mentioned which showed the necessity of a different type of vacuum tube socket. Accordingly, the tube base as described was used in all the oscillators and receivers. When one of these new type tube sockets was placed in the receiver circuit the drift of frequency, due to body capacity of the operator, was cut approximately in half.

The shielding of the two high frequency oscillators was not so successful. The effects of body capacity were eliminated to a great extent but the effect of magnetic coupling between the two oscillators was not eliminated, no matter what degree of shielding was used. Although 1/64 inch copper plate was used, the shield increased the apparent resistance of the oscillators to such a point that at times oscillation would not take place, and if the oscillations did not stop there was a change in frequency due to this added resistance.

It was found impossible to get the 1000-kilocycle beat frequency of the two high frequency oscillators to excite the grid of the 1000-kilocycle oscillator. It was found possible to get the desired beats when the two oscillators were allowed to oscillate while completely shielded from one another. When an inductive or capacitive method of coupling was used to take this 1000-kilocycle beat and to excite the grid of the 1000-kilocycle oscillator, the two high frequency oscillators would sychronize. The theory developed for the effect of resistance, inductance and capacitance can be directly applied to this case where there are two oscillators working in close proximity, and connected by an inductive or capacitive link. From the theory it appears that if the resonant frequency of the two oscillators were the same, there would be no reaction between the two oscillators, i.e., the value of L_1' would be equal to L_1 and the frequency of one oscillator would not affect the frequency of the other oscillator.

If the frequencies of the two oscillators are different by 1000-kilocycles, the theory shows that, when the resonant frequency of oscillator A is higher than the resonant frequency of oscillator B close to it, there will be a reaction between the two oscillators. According to theory, the effect of oscillator B or oscillator A will be to increase the apparent inductance L_1' of oscillator A, while the effect oscillator A on oscillator B will be to decrease the apparent inductance L_2' of oscillator B. This decrease in apparent inductance of the lower resonant frequency oscillator and increase in apparent inductance of the other oscillator will tend to make the apparent inductance of each oscillator approach the same value. Then each oscillator having the same inductive value, all other factors having remained the same, the effect will be resonance between the two oscillators. Experimentation proved this theory very well. In every instance when either an inductive or capacitive coupling was used to take the 1000-kilocycles beat, the frequency of the high frequency oscillator would be lowered and the frequency of the low frequency oscillator would be raised to such a point that the two oscillators would synchronize.

The effects of changes in plate and filament voltages upon the frequency of the radiated wave can best be seen by referring to the graphs of frequency versus plate voltage and of frequency versus filament voltage. Taking first the graph of frequency versus plate voltage, (Plate VI) it can be seen that there was a rapid increase in frequency as the plate voltage was increased.

The frequency readings were taken for this graph with constant filament voltage, starting at 25 volts, the lowest plate voltage at which oscillations could be detected. The maximum voltage used was 165 volts which was the maximum

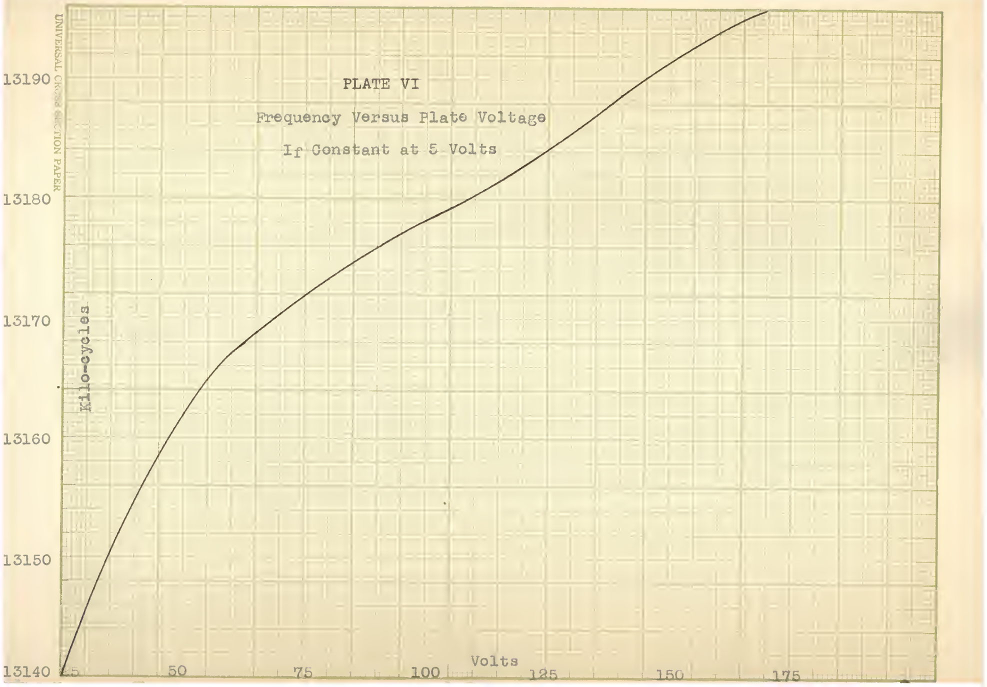


PLATE VI
Frequency Versus Plate Voltage
If Constant at 5 Volts
Kilo-cycles
13190
13180
13170
13160
13150
13140
25
50
75
100
125
150
175
Volts
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output of the B-eliminator used for plate power. Readings were taken in steps of ten volts each. The increase in frequency is due to two causes, one the decrease in the plate resistance of the tube and second the decrease in the interelectrode capacity of the tube. In the formula for resonance in a parallel circuit,

$$\omega = \sqrt{\frac{1}{L\,C} - \frac{R^2}{L^2}}$$ where R is the resistance of the circuit.

It can be seen that the value of ω varies inversely as the resistance of the circuit, also that the frequency varies inversely as the capacity of the circuit. Changing the plate voltage from a lower level to a higher level causes a decrease in its plate resistance. This decrease in resistance is one cause of the increase in frequency. As the resistance of the tube is decreasing, the capacity of the tube is evidently also decreasing, which makes the frequency drift to a higher level.

The graph showing the effect of changes in filament voltage on frequency is Plate VII. The various readings were taken with a constant plate voltage of 100 volts, and the filament voltage starting at four volts, since that was the lowest voltage at which the tube would oscillate. As the voltage was changed from four to five volts, the change in frequency was four kilocycles. Five volts was the rated

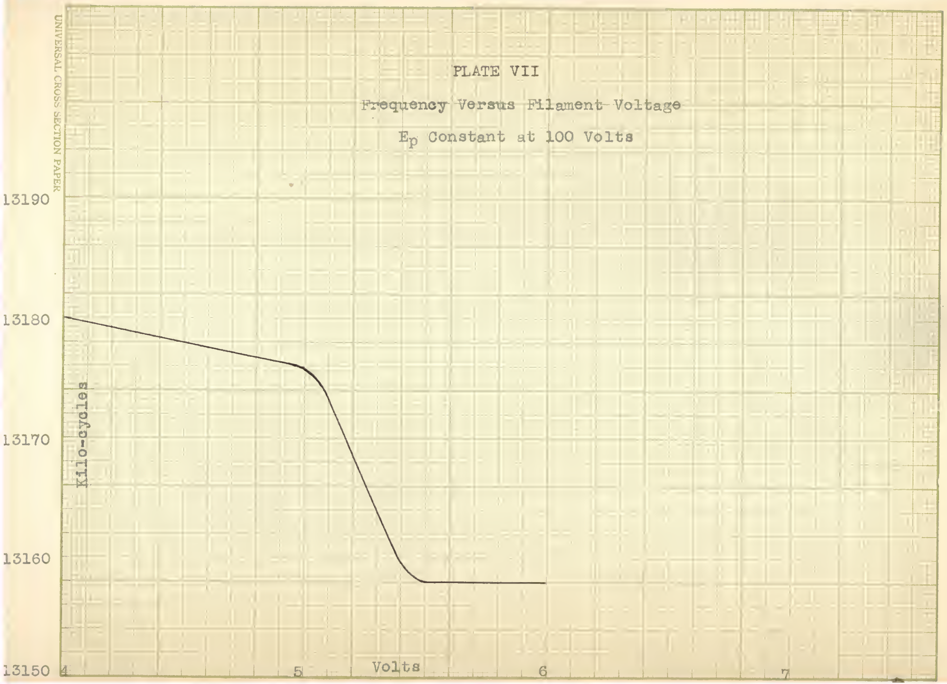

PLATE VII
Frequency Versus Filament Voltage
E_p Constant at 100 Volts
Kilo-cycles
Volts
13190
13180
13170
13160
13150
4
5
6
7
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filament voltage of the tube. When the voltage was increased from five to five and one-half volts, the frequency dropped 18 kilocycles. Then as the voltage was changed from five and one-half to six volts, no change in frequency could be detected, due to the point of current saturation having been reached in the tube. As the filament voltage of a tube is increased at constant plate voltage, the plate resistance of the tube increases. Referring to the formula given above it can be seen that this increase in resistance would cause the frequency to change from a higher to a lower level. This increase in frequency may also be caused by an increase in the input capacity of the tube. This graph shows excellently the small change in frequency when the tube is under-loaded and the large change in frequency when the tube is over-loaded. Under-loading a tube will give better frequency stability, and besides it will not be endangering the life of the tube.

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