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High Stability LC Oscillator for Use With a Capacitive Pressure Sensing Element

Arthur J. Eldridge

LC OSCILLATOR — ELDRIDGE

NAME AND ADDRESS	DATE

HIGH STABILITY LC OSCILLATOR FOR USE WITH A CAPACITIVE PRESSURE SENSING ELEMENT

By

Arthur J. Eldridge

A Thesis
In partial fulfillment of the
Requirements for the Degree of
Master of Science in Electrical Engineering

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1955

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MASTER OF SCIENCE

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DATE 1/19/1956

Thesis committee

R. A. Herzemer Jr.
CHAIRMAN

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

BACKGROUND OF THE PROBLEM

In the course of work at the Sandia Corporation, a definite need arose for the measurement of barometric air pressures to an accuracy beyond that obtainable with commercially available equipment. The standard instrument for measuring these pressures is the mercurial barometer. While a visual method of reading the instrument produced good results to within a 0.1 millimeter of mercury, it was dependent upon the operator using as a reference a target sighting on the top of the meniscus formed in the barometer tube by the mercury. Unfortunately, this meniscus is in itself a source of error of as much as 0.05 millimeter of mercury so that accuracies greater than this could only be achieved by the elimination of the meniscus and thus the elimination of a means of sighting-in accurately on the column.

The elimination of the meniscus, although not a simple matter, was a practical one for its cause was known to be due to foreign matter mainly on the wall of the tube in the form of adsorbed moisture. The solution of this problem, while interesting, is not within the scope of this paper and, therefore, will not be discussed.

With the absence of a meniscus, the visual reading of the mercury column height to accuracies of the order

[illegible]

In the course of [illegible] the [illegible] [illegible], a definite need arose for [illegible] measurements [illegible] air pressure [illegible] [illegible] that [illegible] commercially available [illegible]. The [illegible] instrument for measuring these [illegible] barometer. [illegible] instrument [illegible] millimeter of mercury. [illegible] using [illegible] meniscus [illegible] in the [illegible] for the mercury. Unfortunately, [illegible] meniscus [illegible] error of as much as 0.05 [illegible] accuracy [illegible] the elimination [illegible] of a means of [illegible].

The [illegible] simple matter, [illegible] known to be due to [illegible] the tube in the form of [illegible] of thin [illegible] scope of this [illegible].

With [illegible] of the mercury [illegible]

of 0.01 millimeter of mercury becomes at once an extremely laborious, if not impossible, operation. A preliminary investigation of methods for producing the desired accuracy and simplicity centered around the possibility of using a standard barometer tube in conjunction with some form of electrical sensing element. This transducer would then act to replace the visual method of reading the height of the mercury.

Four possibilities considered were:

1. Photoelectric methods.
2. Variable inductance method.
3. Variable resistance method.
4. Variable capacitance method.

The photoelectric transducer.[1] Photoelectric methods usually take the form of two photocells and a light beam which are maintained in alignment with the surface of the mercury column by a servomechanism. One photocell must be shadowed by the column while the other is not, before the driving mechanism will come to rest. The gear train that positions the photocells also turns a counter which shows the light cell position in units of column height.

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[1]Steven S. Haynes, "Automatic Calibration of Radiosonde Baroswitches," Electronics, 24:126-129, May, 1951.

of 0.01 millimeter [illegible] becomes ex-
tremely [illegible]
preliminary investigation [illegible]
desired accuracy [illegible]
bility of using a standard [illegible]
with some form of electrical [illegible]
transducer would [illegible]
of reading the height of the [illegible].

Four possibilities were considered:

1. Photoelectric [illegible]
2. Variable [illegible]
3. Variable resistance [illegible]
4. Variable capacitance [illegible]

The photoelectric [illegible]
[illegible]
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surface of the [illegible]
[illegible]
is not, before the [illegible]
The [illegible]
a [illegible]
of [illegible].

[illegible]

Disadvantages. This system, however, is subject to errors caused by backlash, friction, and the distance between the photocells. The system also has a dynamic lag when the moving mercury column leaves the mechanism behind.

The variable inductance transducer.[2] Variable inductance, although reasonable in principle, leads to practical difficulties which are of major proportion. One method of measuring the inductance of the column would consist of placing a contact on top of the mercury column and another in the mercury pool at the base of the barometer. The electrical lead from the floating contact would then be brought out a vacuum seal in the top of the barometer tube.

Disadvantages. This lead would have to bend and coil as the floating contact approached the top of the column, which would put a varying force on the surface of the mercury introducing errors. Then, too, friction between the contact and the tube wall would produce an additional and unpredictable error.

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[2]Howard C. Roberts, "Mechanical Measurements by Electrical Methods," (Pittsburgh: The Instruments Publishing Company, Inc., 1951), p. 61.

Dis[illegible] [illegible] [illegible] [illegible]
to [illegible] [illegible] [illegible] [illegible] [illegible]
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barometer. The [illegible] [illegible] [illegible] [illegible]
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barometer [illegible].

Dis[illegible] [illegible] [illegible] [illegible]
coil as the [illegible] [illegible] [illegible] of the
column, [illegible] [illegible] [illegible] [illegible]
of the [illegible] [illegible] [illegible]
between the [illegible] and [illegible] [illegible]
additional and [illegible] [illegible].

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[2] Howard [illegible] [illegible] [illegible]
Electrical [illegible] [illegible] [illegible]
Publishing Company, [illegible] [illegible]

Variable resistance.[3] The variable resistance method would consist basically of using the mercury column to short out a resistance in the form of a wire or coating on the tube wall. This resistance would then be measured very accurately with a precision resistance bridge.

Disadvantage. It was felt, however, that the resistance would produce contamination of the mercury column which would result in erroneous readings.

Variable capacitance.[4] This method consisted of using the mercury column as a variable capacitance by placing a conducting surface on the outside wall of the barometer tube. Thus, the tube itself would form the dielectric medium of the capacitor; the mercury column would act as the movable plate, and the coated surface as the fixed plate. (Refer to Figure 1 for illustration). This variable capacitor could then be measured by some means such as a precision capacitance bridge, or used to vary the frequency of an oscillator which would then be an indication of column height.

---

[3] H. J. Svec and D. S. Gibbs, "Recording Mercurial Manometer for Pressure Range 0-760 mm Hg," Review of Scientific Instruments, 24:202-204, March, 1953.

[4] R. S. Jamieson, "A Capacitive Manometer," (Sandia Corporation Technical Memorandum No. 21-54-53, Albuquerque, New Mexico, 1954), pp. 3-4.

Variable resistance.[3] The variable resistance method would consist basically of using the mercury column to short out a resistance as the level of mercury or [illegible] of the [illegible]. This resistance could then be measured very accurately by means of a resistance bridge.

Disadvantages. [illegible] resistance would produce [illegible] column which would [illegible].

Variable capacitance.[4] It has been suggested of using the mercury column as a variable capacitance by placing a conducting surface on the outside wall of the barometer tube. Since the tube walls would serve the dielectric medium of the capacitor, the mercury column would act as the movable plate, and the outer surface as the fixed plate. [illegible] This variable capacitance could then be measured by some means such as a [illegible] bridge, or used to vary the frequency of an oscillator which would then be an indication of column height.

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[3] [illegible] *Review of Scientific Instruments*, [illegible]

[4] [illegible] Corporation [illegible] New Mexico, [illegible]

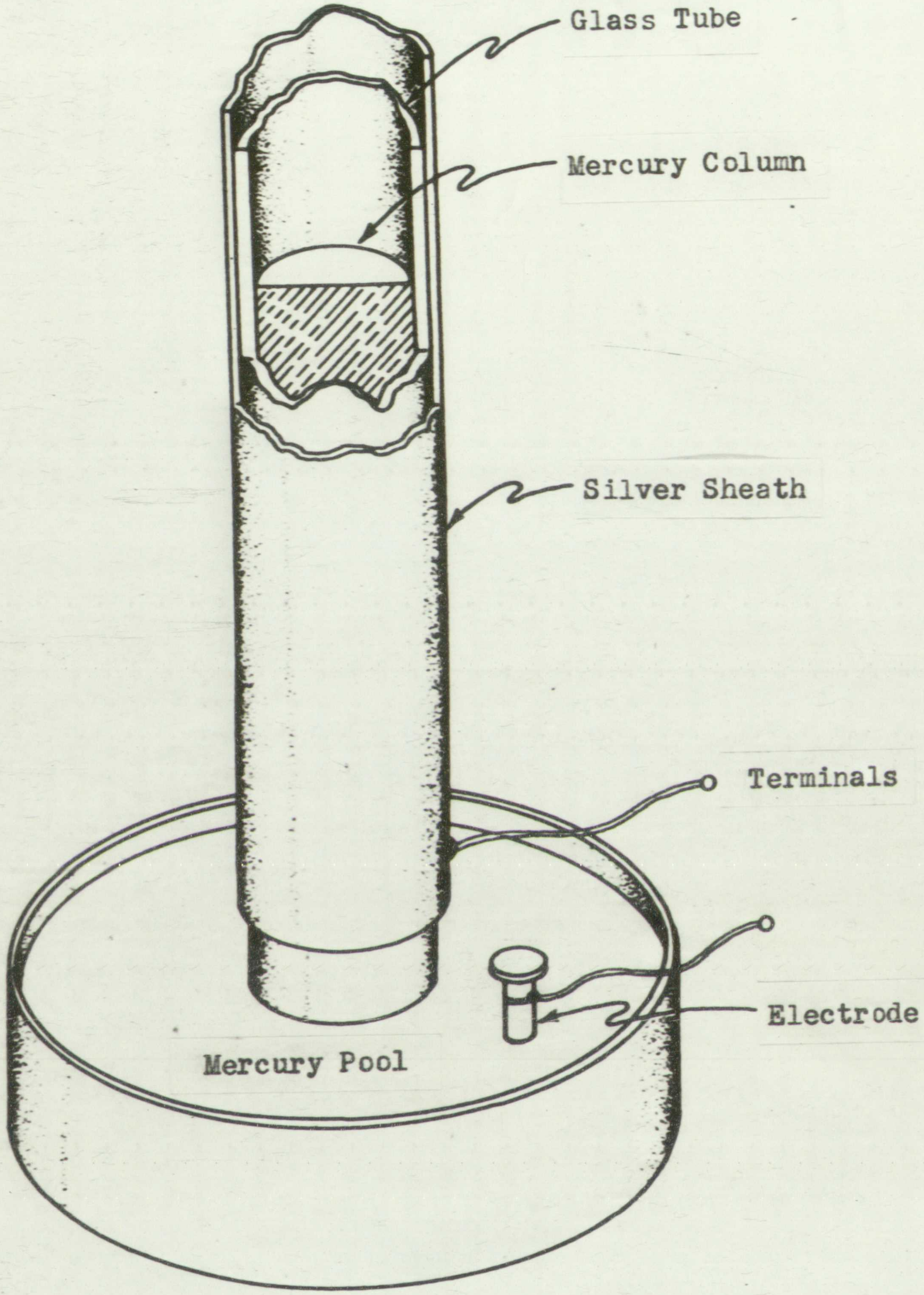

Figure 1 CROSS SECTIONAL VIEW OF CAPACITIVE MERCURIAL MANOMETER

The last of the four methods considered seemed the most desirable since it would have practically no dynamic lag, no hysterisis, and would not affect the mercury in any physical or chemical manner. It was further felt that the use of a variable oscillator would be superior to that of a bridge method of measurement for several reasons.

1. The proper use of a high precision capacitance bridge requires operator skill and experience.

2. These bridges are very expensive to acquire and are made only on special order, so that delivery is usually quoted as six or eight months after placement of an order.

3. The oscillator method readily adapts itself to an automatic readout and printout display so that the information for any setting of the barometer may be permanently retained. This is accomplished by feeding the oscillator output to a frequency counter to which a printer, with a direct digital display, may be attached. (See Figure 2 for a block diagram of proposed system). Operator error is then confined to the reading of this display plus its translation from a frequency count to a column height by a set of appropriate tables.

4. The operation may be performed by a relatively inexperienced operator.

The last of the four methods outlined, seemed the most desirable since it would have practically no dynamic lag, no hysteresis, and would not disturb the mercury in any physical or chemical manner. It was further felt that the use of a separate oscillator would be superior to that of a bridge method of measurement for several reasons.

1. The proper use of a radio frequency or capacitance bridge requires considerable skill and experience.

2. These bridges are very expensive and require [illegible] and are made only on special order, so that delivery is usually quoted as six or eight months after placement of an order.

3. The oscillator method readily lends itself to an automatic readout and permanent [illegible] information for any setting of the [illegible] permanently retained. This is accomplished by [illegible] the oscillator output to a frequency counter and a printer, with a direct or [illegible] (See Figure 2 for a block diagram of proposed system.) Operator error is then confined to [illegible] display plus its transmission [illegible] a column height by a set of [illegible] tables.

4. The operation may be performed by a relatively inexperienced operator.

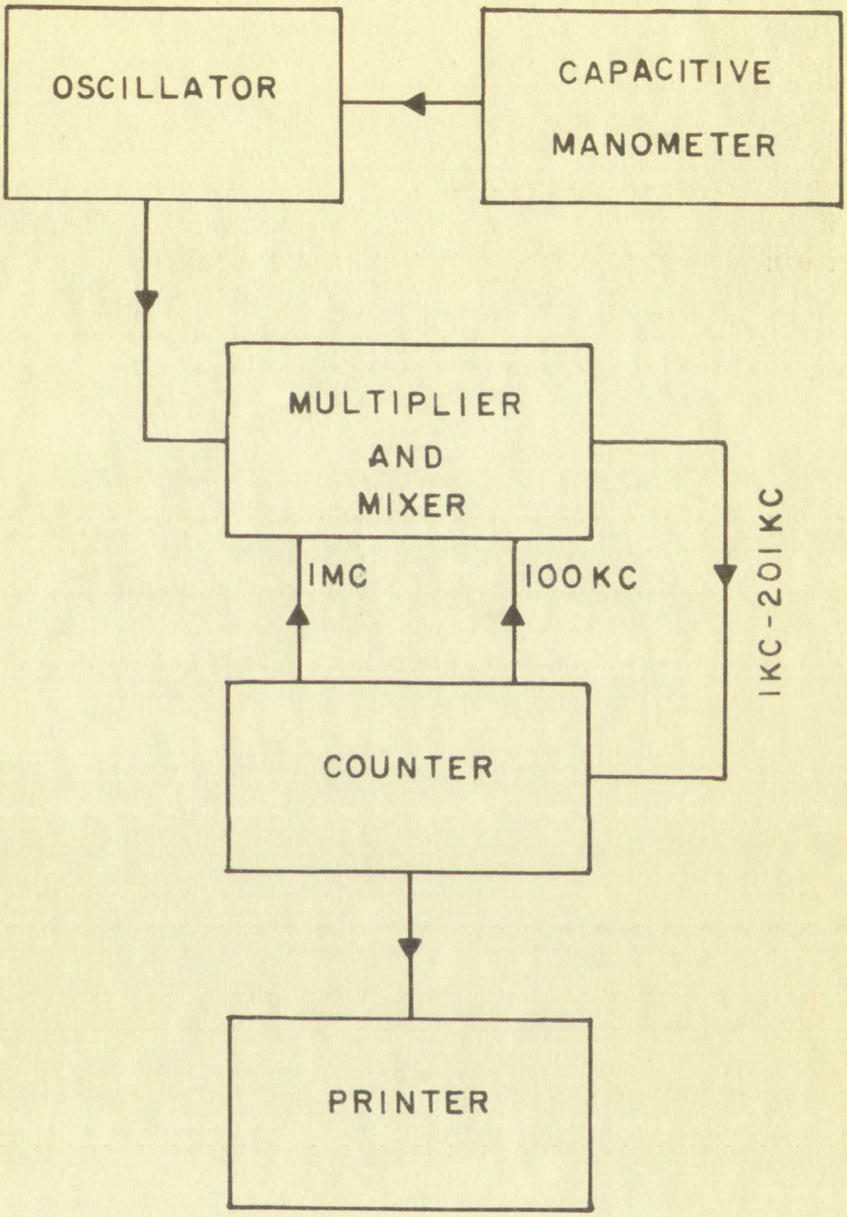

FIGURE 2 BLOCK DIAGRAM OF COMPLETE SYSTEM

THE PROBLEM

When the preceding decisions were reached, the problem of the development of the necessary oscillator and associated electronic circuitry was presented to the investigator for solution with the following stipulations:

(a) The system must possess necessary resolution and stability to produce readings accurate and reproducible to 0.01 millimeter of mercury.

(b) Operation must be simple so that an operator unfamiliar with electronics could operate it satisfactorily.

(c) It must not be prohibitively expensive.

The basic problem was one of oscillator stability. To achieve success, it was deemed essential to build a highly stable, yet variable, oscillator. Unfortunately, a crystal oscillator could not be used; although these oscillators have been known to yield stabilities in the order of 1 part in 10^8 per hour or better, they cannot be made to vary more than a fraction of a per cent from their operating frequency.

It was necessary, therefore, to investigate the possibility of using a non-crystal type resonator in the oscillator circuit. In the field of sinusoidal oscillators, there are two classes of this type of oscillator circuit; the negative resistance oscillator, usually

referred to as the dynatron, and the positive feedback type wherein the output signal of an amplifier is fed through a frequency selective network, thence into the input of the amplifier. The latter type may assume many forms, such as the Hartley, Colpitts, and Phase Shift, to give a few examples. In this study, as previously mentioned, stability of frequency is of prime importance. Therefore, an investigation was made to determine which type of oscillator was inherently the most stable.

As far back as 1923, efforts were made to produce frequency stable variable oscillators for use in airborne transmitters.[5] Most of this work met with little success until it was discovered that changing vacuum tube impedances influenced frequency stability to a considerable extent. Once this fact was appreciated, a number of investigators proposed schemes for minimizing the effect. These various proposals contained certain disadvantages, as well as advantages, which must be taken into account when used for any particular application.

Of the highly stable variable oscillators in known existence, the study was narrowed down to two

---

[5]Ross Gunn, "A New Frequency-Stabilized Oscillator System," Proc. I.R.E., 18:1560. (September, 1930).

referred to as the dynatron, and the positive feedback type wherein the output signal of an amplifier is fed through a frequency selective network, thence into the input of the amplifier. The latter type may assume many forms, such as the Hartley, Colpitts, and Tuned Plate, to give a few examples. In this study, as previously mentioned, stability of frequency is of prime importance. Therefore, an investigation was made to determine which type of oscillator was intrinsically the most stable.

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Of the highly stable variable oscillators in known existence, the Clapp was [illegible]

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[5] Ross Gunn, "A [illegible] Oscillator System," Proc. I.R.E., [illegible] (November, 1930).

which appeared to be the simplest to construct and maintain with a minimum number of adjustments. The two circuits are discussed in detail in Chapter II where a choice between them is made and reasons for the selection are given.

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tain with a minimum [illegible]. The two
circuits are discussed in detail, [illegible]
a choice between them is made and reasons for this
selection are given.

CHAPTER II

EXPERIMENTAL SEARCH FOR THE DESIRABLE OSCILLATOR

The desirable type of oscillator. It was immediately recognized that an LC type resonator would be essential because phase shift and bridge type oscillators using resistance usually require the variation of more than one element simultaneously or are comparatively complex in their construction. This, then, means that any change in capacity would be reflected as a corresponding change in frequency, given by the equation:

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

for the circuit of Figure 3 below:

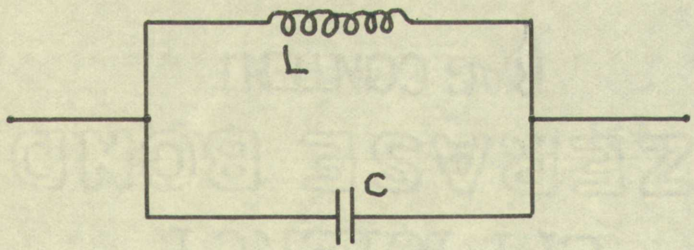

Figure 3. Parallel Resonant LC Circuit

Choice of circuits. The literature was then searched for information on high stability LC oscillators.

CHAPTER [illegible]

EXPERIMENTAL SEARCH FOR THE [illegible] [illegible]

The desirability of [illegible]. [illegible] immediately recognized that [illegible] would be essential because [illegible] lators using resistance [illegible] more than one element [illegible] complex in their construction. [illegible] any change in capacity [illegible] sponding change in frequency, given by the [illegible]

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for the circuit of Figure [illegible] below:

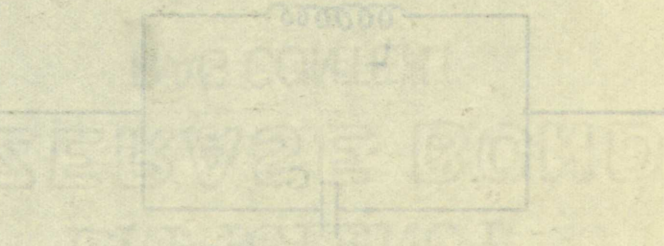

Figure 3. [illegible]

Choice of circuits. [illegible] searched for information [illegible]

The first source of information covered was, "Vacuum Tube Oscillators."[6] This book is a rather general treatise on the theory, operation, and design of vacuum tube oscillators of just about all the main categories. A search of this text indicates two favorable approaches:

(1) The Franklin Oscillator

(2) The Gouriet - Clapp Oscillator

These two circuits were constructed in the laboratory while theoretical studies were continued.

Short-term stability. The advantages of an inherently good system will only be obtained if the parameters of all elements in the system have excellent short-term stability. For the purposes of this project, all other sections of the system were considered to be constant, or reasonably so, and the limiting accuracy was considered to be that of the oscillator stability within that period herein referred to as short-term. As a minimum, a short-term period would actually be the time required for the operator to make one run. This time has been estimated not to exceed one minute.

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[6]William A. Edson, Vacuum Tube Oscillators, (New York: John Wiley and Sons, Inc., Copyright 1953).

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[6] William A. Edson, Vacuum Tube Oscillators (New York: John Wiley and Sons, Inc., [illegible]).

But this is only the time required for one run. If a number of points needed checking, obviously more time would be consumed. So, on a purely arbitrary basis, short-term has been defined as one hour. Such a period should not be excessively restrictive on the requirements for short-term stability of the oscillator.

Having defined short-term stability, the question now arises as to just what this stability must be. Intimately connected with stability is center frequency of operation. Stability may be defined as deviation from the operating frequency, expressed as a ratio. For the purposes of this paper, that definition will be used.

The Franklin Oscillator. Edson states the Franklin Oscillator has excellent stability. A cursory examination of the circuit, Figure 4, indicates that an astable multivibrator has one of its two alternating current feedback paths controlled by a tuned or parallel resonant LC circuit. C_x and L form the parallel resonant circuit that determines frequency of operation. C_1 and C_2 are very small capacities to provide low coupling between the tank circuit and the driving system. If the amplitude of the driving system is somehow limited to a low value, the tank constants will not be affected by heating effects and maximum stability is attained.

But this is only the time required for one run. If a number of points needed checking, obviously more time would be consumed. So, for a majority of very practical uses, short-term has been defined as one hour. Such a period should not be excessively restrictive on the requirements for short-term stability of the oscillator.

Having defined short-term stability, the question now arises as to just what this quantity most intimately connected with stability is — namely frequency of operation. Stability may be defined as deviation from the operating frequency, expressed as a percent. For the purposes of this paper, that definition will be used.

The Franklin Oscillator. Long established, the Franklin Oscillator has excellent stability. A cursory examination of the circuit, Figure 4, indicates that a normal multivibrator has one of its two alternating feedback paths controlled by a high Q parallel resonant LC circuit. C_t and L form the parallel resonant circuit that determines frequency of operation. C_1 and C_2 are very small capacities to provide low coupling between the tank circuit and the driving system. If the tank is loosely coupled, the driving system is effectively looking into a low value, the tank constants will not be affected by driving circuits and maximum stability is obtained.

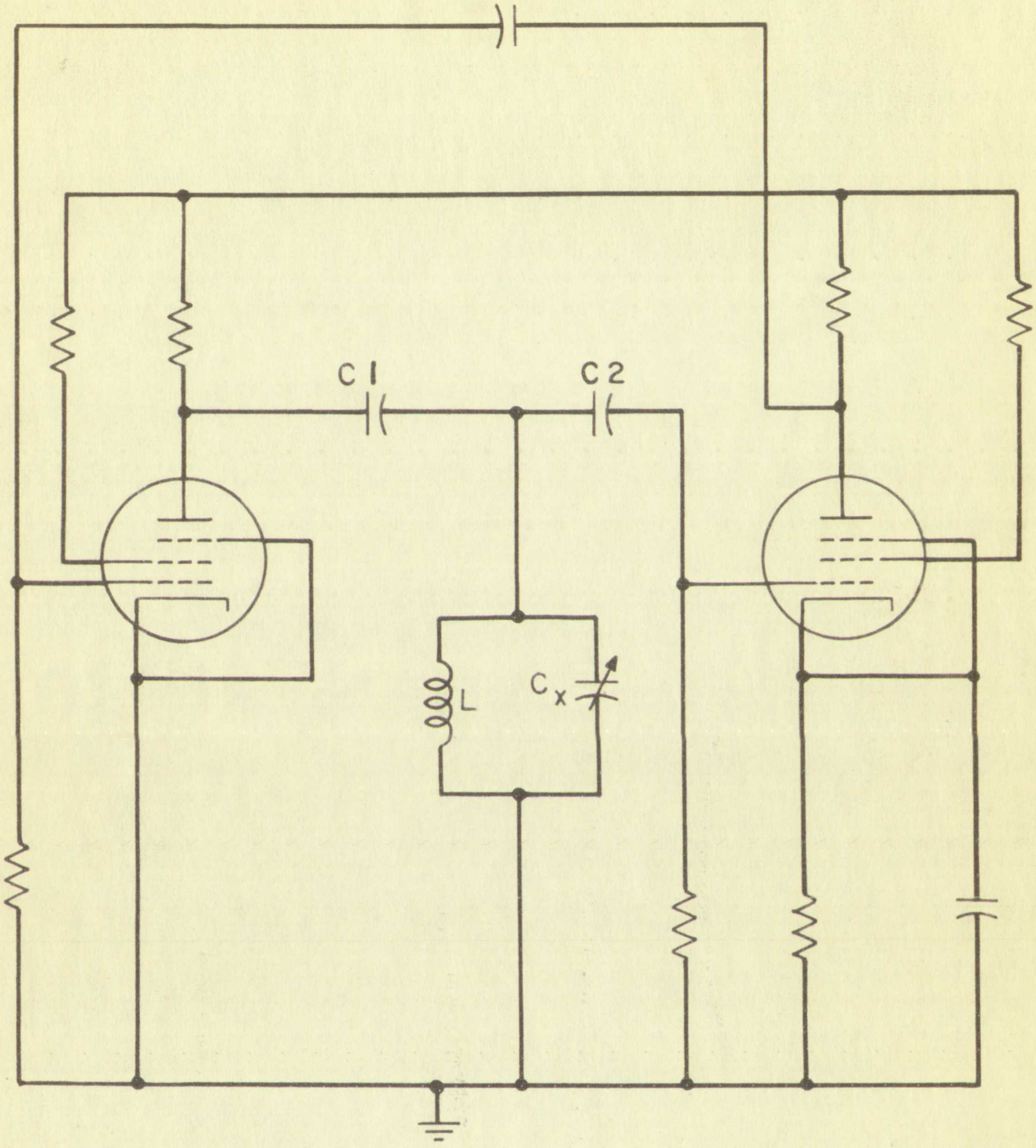

FIGURE 4 FRANKLIN OSCILLATOR

The laboratory model failed to provide the required stability and was quite unstable above approximately one megacycle. Oscillation above two megacycles proved unobtainable. The short-term drift amounted to as much as several hundred parts per million and this stability was unattainable until considerable aging took place.

The Gouriet - Clapp Oscillator. Work on the Franklin Oscillator was abandoned when it was observed that the Gouriet - Clapp Oscillator appeared to have less drift. So a concentrated effort was made to improve the stability of the first laboratory model of the unit.

The general design equations and a description of this oscillator are given by Gouriet.[7] This oscillator is an outgrowth of a circuit that used a crystal for a resonator commonly referred to as the Pierce Oscillator. The derivation of the Gouriet - Clapp from the Pierce Oscillator is shown schematically in Figures 5, 6, and 7. By replacing the crystal with a parallel resonant LC circuit, J. K. Clapp converted the Pierce to a high stability LC oscillator.[8] This work was performed independently by G. G. Gouriet in England.

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[7]G. G. Gouriet, "High-Stability Oscillator," Wireless Engineer, 27:105-112, (April, 1950).

[8]J. K. Clapp, "An Inductance-Capacitance Oscillator of Unusual Frequency Stability," Proc. I.R.E., 36:356-358, (March, 1948).

The laboratory model failed to provide the required stability and was quite unstable above approximately one megacycle. Consequently, more extensive stability proved unobtainable. The short term drift was erratic as well as several jumps in frequency and this instability was unaccountable until [illegible] took place.

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[7] G. G. Gouriet, "High Stability Oscillator," Wireless Engineer, 27:105-112 (April, 1950).

[8] J. K. Clapp, "An Inductance-Capacitance Oscillator of Unusual Frequency Stability," Proc. I.R.E., 36:356-358 (March, 1948).

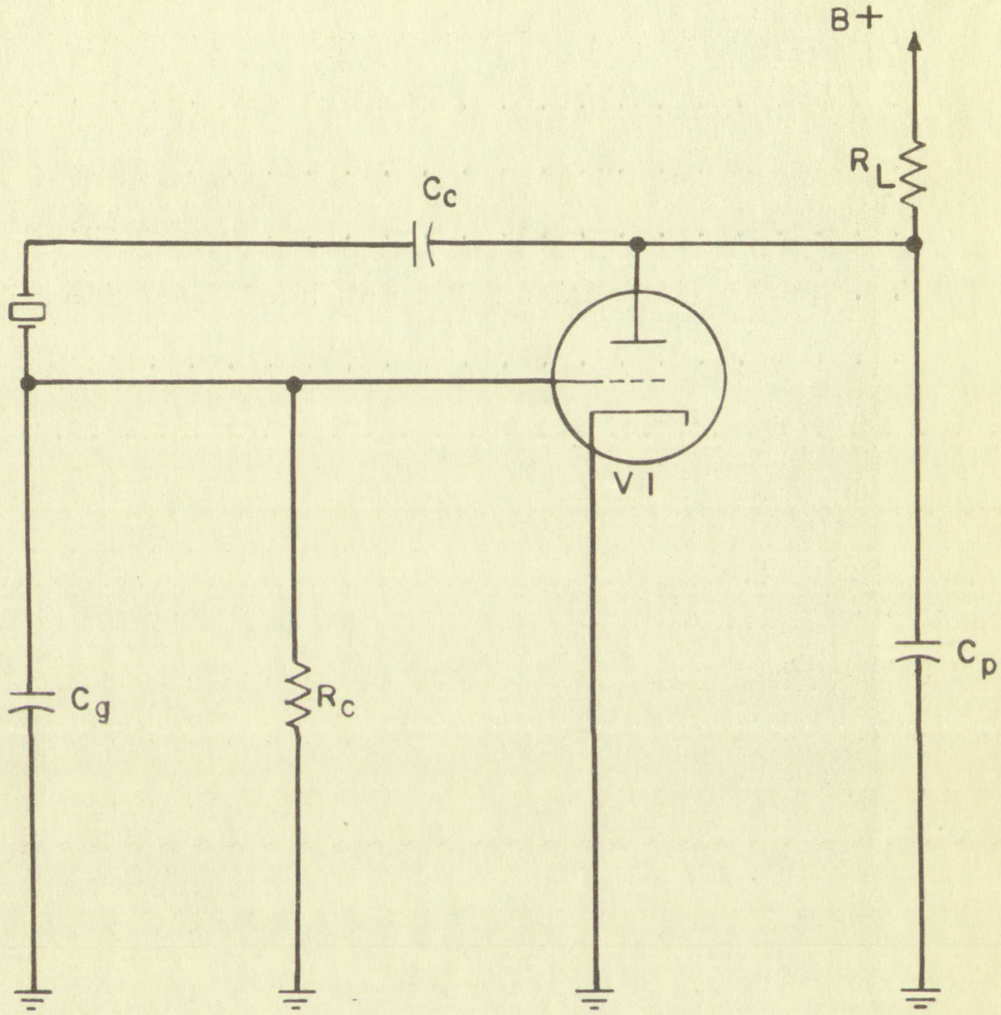

FIGURE 5 PIERCE OSCILLATOR

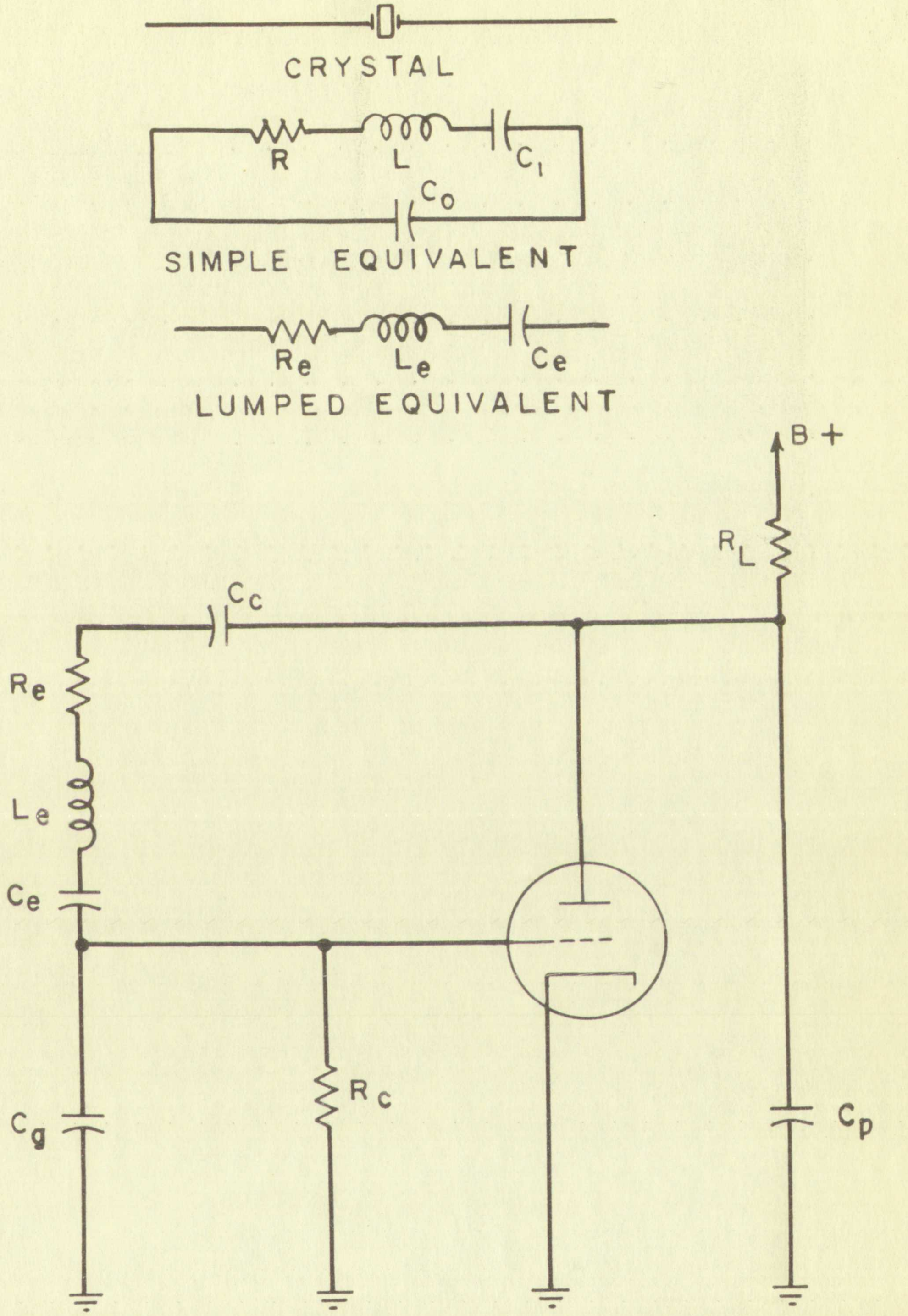

FIGURE 6 IDEALIZATION FOR ANALYSIS

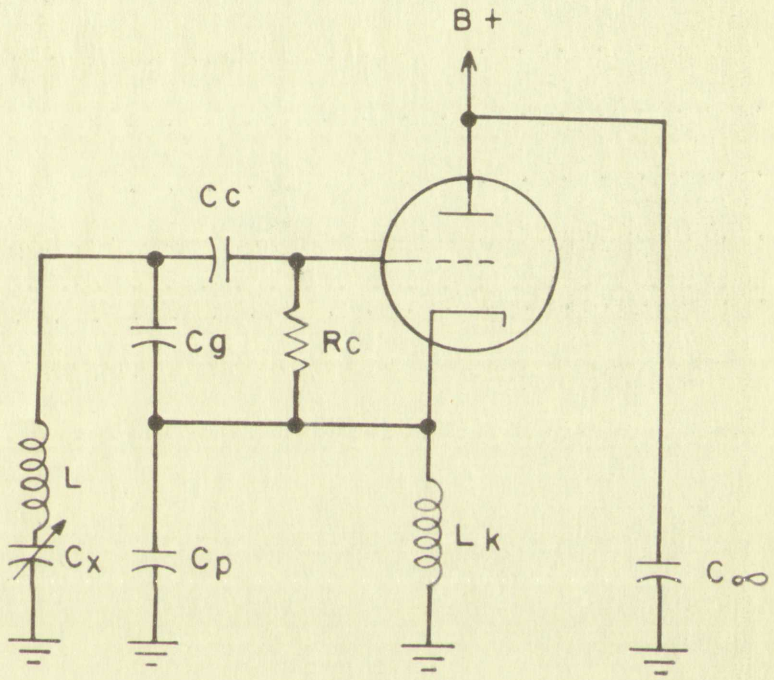

FIGURE 7 GOURIET-CLAPP OSCILLATOR

Shown in Figure 8 is a schematic diagram of the first circuit constructed. Frequency stability on a short-term basis was about one hundred parts per million. Amplitude of oscillation was high and it was felt that by decreasing this so that internal heating effects in the inductor were small, drift could be improved. Further, physical placement of components left much to be desired as far as heating was concerned. That is, the tank inductor, capacitors, and tubes were all mounted on the same side of the chassis. Thus, heating effects were quite pronounced. It was decided to rebuild the circuit with the vacuum tube or tubes on one side of the chassis and the tank circuit on the other side. The chasis was placed in a vertical position with one end cut off so that convection currents could cool the tube and conduct heat away from the tank circuit components.

Factors affecting stability. At this point, it may be well to enumerate the major factors affecting frequency stability. The first factor, a somewhat obvious one, is the tank circuit Q. The higher the Q of the resonator, the more stable will be the oscillator; the reason for this being the rapidity of change of phase angle of the resonator impedance with change in

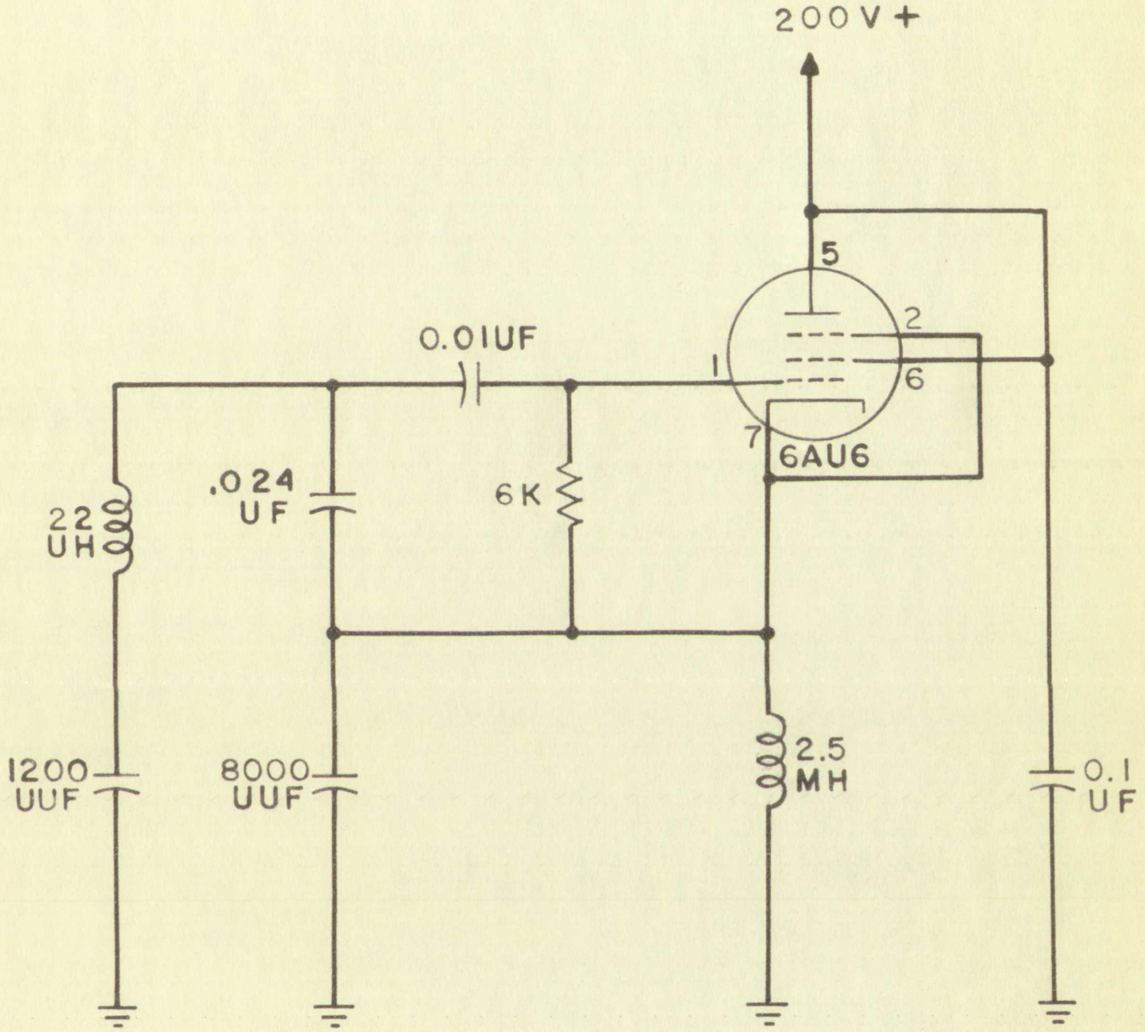

FIGURE 8 ACTUAL VALUES USED IN FIRST LABORATORY MODEL OF GOURIET-CLAPP OSCILLATOR

frequency.[9] The higher the Q, the greater will be this change.

The second factor is temperature effect. Resistors, capacitors, and inductors all have temperature coefficients. These coefficients may be either positive or negative.[10] Temperature changes result in dimensional changes in chassis and components. Good design will minimize, but never eliminate, these effects.

A third factor affecting stability is change of supply voltage. Change in frequency with respect to changes in supply voltage can be minimized. The derivation of an expression for those factors contributing to this instability will therefore be of considerable aid in such an analysis. Fair has derived an equation expressing this relationship.[11]

$$\frac{d\omega}{dv} = \frac{\frac{1}{\mu}\frac{\partial\mu}{\partial v} X_p X_g (X_L - X_x)}{\left(1 - \frac{X_p}{\mu X_g}\right)\left[\frac{\partial X_p}{\partial\omega} + \frac{\partial X_g}{\partial\omega} + \frac{\partial(X_L - X_x)}{\partial\omega}\right] r_p r_g}$$

---

[9] Britton Chance, et al, Waveforms, 19:128, Radiation Laboratory Series, (New York: McGraw-Hill Book Co., Inc., 1949), Sec. 4-10.

[10] Edson, loc. cit.

[11] I. E. Fair, "Piezoelectric Crystals in Oscillator Circuits," The Bell System Technical Journal, 24:161-215, (April, 1945).

frequency [illegible]
change.

The [illegible]
capacitor, [illegible]
limitation. [illegible]
negative [illegible]
changes in voltage [illegible]
minimize, but [illegible]

A [illegible]
supply voltage [illegible]
changes in [illegible]
values of an [illegible]
so that [illegible]
and in [illegible]
expression [illegible]

$$\frac{d\omega}{dv} = \text{[illegible]}$$

Radio [illegible]
Book [illegible]

Labor [illegible]
[illegible]

From which it may be observed that best stability with changing voltage ensues when:

1. r_p and r_g are large.
2. X_p and X_g are small.
3. X_L and X_x are small.
4. $\mu = g_m r_p$ is large.

where r_g and r_p are internal dynamic tube resistances, X_p and X_g are the reactances of C_p and C_g respectively on Figure 7.

Although the above equation is significant from a quantitative standpoint, it does not explain physically why a voltage change produces a frequency change. The key is in the method of producing oscillation. In a pi type oscillator such as a Hartley or Colpitts, the plate and grid resistances of the tube are shunted across elements of the tuned circuit. Changes in supply voltage cause changes in plate and grid resistances, thus changes in frequency. The Gouriet-Clapp oscillator minimizes this effect by tapping into a portion of the resonator where the impedances are very low. Therefore, slight changes in grid and plate resistance have little effect on frequency. The basic idea is illustrated in Figure 9. It will be observed that C_g and C_p are considerably larger than C_x. This same principle may be accomplished

From which it may be observed that best stability with changing voltage ensues when:

1. r_p and r_g are large.
2. X_p and X_g are small.
3. X_L and X_x are small.
4. $\mu = g_m r_p$ is large.

where r_g and r_p are internal dynamic tube resistances, X_p and X_g are the reactances of C_p and C_g respectively in Figure 7.

Although the above [illegible] is satisfactory from a quantitative standpoint, it does not explain physically why a voltage change produces a frequency change. The key is in the method of producing regeneration. In a [illegible] type oscillator such as a Hartley or Colpitts, the plate and grid resistances of the tube are connected across elements of the tuned circuits. Changes in operating voltage cause changes in plate and grid resistance, hence changes in frequency. The Gouriet-Clapp oscillator minimizes this effect by tapping into a part of the tuned circuit where the impedances are very low. Therefore, large changes in grid and plate resistances have little effect on frequency. The basic circuit is illustrated in Figure 8. It will be observed that C_1 and C_2 are both very much larger than C_x. This same principle can be

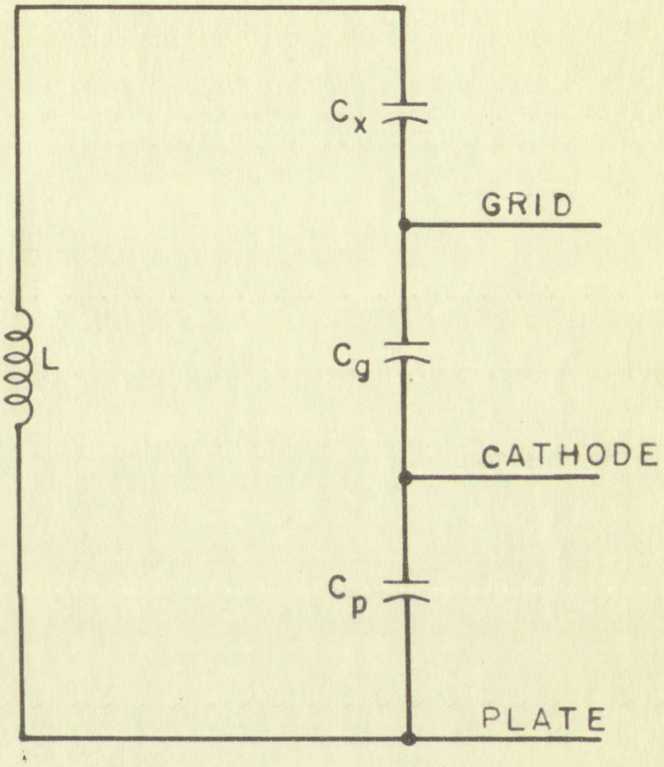

FIGURE 9 ILLUSTRATION OF TAPPING INTO RESONATOR AT ITS LOW IMPEDANCE POINTS

by tapping into the inductor instead of the capacitor.[12]

An additional advantage gained by tapping into low impedance points of the resonator is minimizing the effect on frequency of the varying tube capacitances. It is a well known fact that the grid to cathode and plate to cathode capacitances of a physically realizable vacuum tube are not constants, but vary somewhat during operation of the tube. This effect is due to aging and thermal currents within the tube. Variation of tube capacitance constitutes a very small fraction of the total shunting capacitance since C_g and C_p are very much greater in physical size.

A fourth factor affecting stability is harmonic generation.[13] Apparently, the harmonics generated by the oscillator cross modulate one another to produce a fundamental which is out of phase with the normal mode fundamental being generated. This, then, makes the circuit very sensitive to the amount and distribution of the harmonics produced. Two ways of minimizing this effect are to:

(a) Employ a tank circuit of very high Q so that

---

[12] G. F. Lampkin, "An Improvement in Constant-Frequency Oscillators," Proc. I.R.E., 27:199, (March, 1939).

[13] Frederick E. Terman, Radio Engineers' Handbook, First Edition, Sec. 6, par. 3, p. 488, (New York: McGraw-Hill Book Co., Inc., 1943).

by tapping into the inductor portion of the oscillator.

An additional advantage gained by tapping into low impedance points in the resonant circuit is the effect on frequency of the varying tube capacitance. It is a well known fact that the grid to cathode, plate to cathode capacitance, and grid to plate capacitance of a vacuum tube are not constants, but vary during the operation of the tube. This change is due to the space charge and thermal currents within the tube. Variation of tube capacitance contributes a very small effect if the external shunting capacitance across C_g and C_p are very much greater in physical size.

A fourth factor affecting stability is harmonic generation.[13] Apparently, the harmonics generated in the oscillator cause voltages not necessarily in phase with the fundamental which is out of phase with the original fundamental being generated. This, then, makes the circuit very sensitive to the amount and distribution of the harmonics produced. Some ways of minimizing this effect are to:

(a) Employ a tank circuit of very high Q [illegible]

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[12] G. F. Lampkin, "An Improvement in Constant Frequency Oscillators," *Proc. I.R.E.*, 27:199 (March, 1939).

[13] Frederick E. Terman, *Radio Engineers' Handbook*, First Edition, Section [illegible], par. [illegible] (New York: McGraw-Hill Book Co., Inc., 1943).

the impedance presented to harmonics is low by comparison to the fundamental.

(b) Operate the oscillator at as low an amplitude as possible so as to work the tube on a comparatively linear portion of its characteristic curve.

Two additional factors which affect frequency stability are the photoelectric effect, and vibration to which microphonic tubes are especially susceptible.

The photoelectric effect manifests itself particularly when daylight falls on the oscillator tube. It is not serious, however, and can be easily eliminated by proper optical screening. The frequency shift caused by daylight seems principally due to ultra violet light since artificial light sources of reasonable intensity, such as the light from a one hundred watt incandescent lamp, produced no change.[14]

Very little trouble was encountered due to vibration. Microphonics in circuits or tubes usually is not a severe problem when low impedance circuitry is employed. The power supply consisted of a unit separate from the oscillator chassis. Thus, vibration from transformers or chokes was essentially eliminated.

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[14] Norman Lea, "Notes On The Stability of LC Oscillators," I.E.E. Journal, 92:261-274, No. 20, par. 2.7, par. 3.4, (December, 1948).

The elements of the frequency determining circuit, both L and C, should be chosen for maximum stability. The resonator used for the oscillator circuit investigation took the form of an impregnated coil of wire and silvered mica capacitors. The impregnation used consisted of mica filled polyester resin. The purpose being to hold down rapid temperature variations in the coil by providing a thermal lag or resistance to external temperature changes. The powdered mica served the purpose of decreasing the coefficient of expansion of the resin. Number ten tin coated copper wire was used to provide a relatively good Q. Although it was realized that the arrangement had some serious drawbacks, the thought was kept in mind that if the circuit as a whole proved useful, a concentrated effort at improving resonator performance could then be made.

Feedback Circuits. Since from the previous considerations, it is apparent that some means of harmonic elimination was necessary, a study of feedback circuits was initiated.

Moullin[15] proposed to eliminate harmonic effects by building the oscillating circuit in such a fashion that

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[15] E. B. Moullin, "Effect of Curvature of the Characteristic on Frequency of Dynatron Generators," I.E.E. Journal, 73:186-95, (August, 1933).

The elements of this frequency determining network, both L and C, should be chosen for maximum stability. The resonator used for the model [illegible] investigation took the form of an [illegible] with silvered mica capacitors. The [illegible] consisted of mica filled polystyrene [illegible] down rapid temperature variations [illegible] a thermal lag or resistance to external [illegible]. The powdered mica served the purpose of [illegible] coefficient of expansion of the [illegible] coated copper wire was used to provide a [illegible] Q. Although it was realized that the arrangement had some serious drawbacks, the thought was [illegible] that if the circuit as a whole proved [illegible] effort at improving resonator performance could then be made.

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15 E. B. Moullin, "Effect of Curvature of the Characteristic on Frequency of Dynatron Generators," I.E.E. Journal, 73:[illegible], ([illegible]).

the harmonics were short-circuited. Any good oscillator will do this to a certain extent, but is always limited by resistive components in physically realizable elements.

Arguimbau[16] recognized the effect of harmonics and proposed to eliminate them by operating the vacuum tube as a linear amplifier. This was done by rectifying a portion of the output to furnish grid bias to the vacuum tube in order to limit the amplitude. In effect, this is a variable transconductance method. This method is used quite often for oscillator amplitude control at fixed frequencies, but is not practical for variable frequency use. In spite of rectification of the sine wave, some AC components pass through practical rectifiers and unless the circuits are constructed with extreme care, so that phase shift through the amplifiers is zero, positive feedback results. To accomplish zero phase shift over a spectrum in the megacycle range is quite a task.

Meacham[17] utilized a thermal element as an amplitude control. By incorporating the control as a component

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[16] L. B. Arguimbau, "An Oscillator Having a Linear Operating Characteristic," Proc. I.R.E., 21:14, (January, 1933).

[17] L. A. Meacham, "The Bridge Stabilized Oscillator," Bell System Technical Journal, 17:574, (October, 1938), also Proc. I.R.E., 26:1278-1294, (October, 1938).

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[16] L. B. Arguimbau, "An Oscillator Having a Linear Operating Characteristic," Proc. I.R.E., 21:[illegible], (January, 1933).

[17] L. A. Meacham, "The Bridge Stabilized Oscillator," Bell System Technical Journal, 17:[illegible], (October, 1938); also Proc. I.R.E., 26:1278-1294, (October, 1938).

of a bridge circuit, he was then able to make use of the full gain of the amplifier. Further, thermal control eliminates changes of the tube capacitances which are inherent in automatic gain control involving vacuum tubes.

<u>The Bridge Feedback Circuit</u>. In an attempt to utilize the principles set forth by Meacham, the feedback circuit illustrated in Figure 10 was built. The bridge is connected in such a manner that if the amplitude of oscillation is larger than desirable, a signal one hundred and eighty degrees out of phase with the oscillations in the tank circuit would heavily load the tank, thereby decreasing the signal. If, on the other hand, the signal is smaller than desirable, an in-phase signal is applied to the tank and oscillation will increase in amplitude. At some point, fixed by the constants of the circuit, equilibrium is achieved.

Unfortunately, phase shift not only in the fundamental but in the harmonics so complicated the waveform that the circuit proved unsatisfactory. An additional deficiency of this circuit will be discussed in connection with the next circuit studied.

<u>Positive Coefficient Thermistor Feedback Circuit</u>. The next circuit tried is shown in Figure 11. A signal from the oscillator is amplified, rectified and filtered.

of a bridge circuit, is [illegible] than unity [illegible] the full gain of the amplifier. Further, [illegible] eliminates changes of the tube [illegible] inherent in [illegible] tubes.

<u>The [illegible] Feedback Circuit.</u> [illegible] utilize the [illegible] back circuit [illegible] in Figure [illegible] bridge is connected in such a manner that [illegible] tude of oscillation is [illegible] one hundred and eighty degrees out of phase [illegible] oscillations in the [illegible] tank, thereby decreasing the [illegible] hand, the signal is [illegible] signal is applied to the [illegible] crease in amplitude. At [illegible] of the circuit, equilibrium is [illegible].

Unfortunately, [illegible] mental but in the [illegible] that the circuit proved [illegible] deficiency of this circuit [illegible] with the next circuit [illegible].

<u>Positive [illegible]</u>

The next circuit [illegible] shown in Figure [illegible] from the oscillator [illegible]

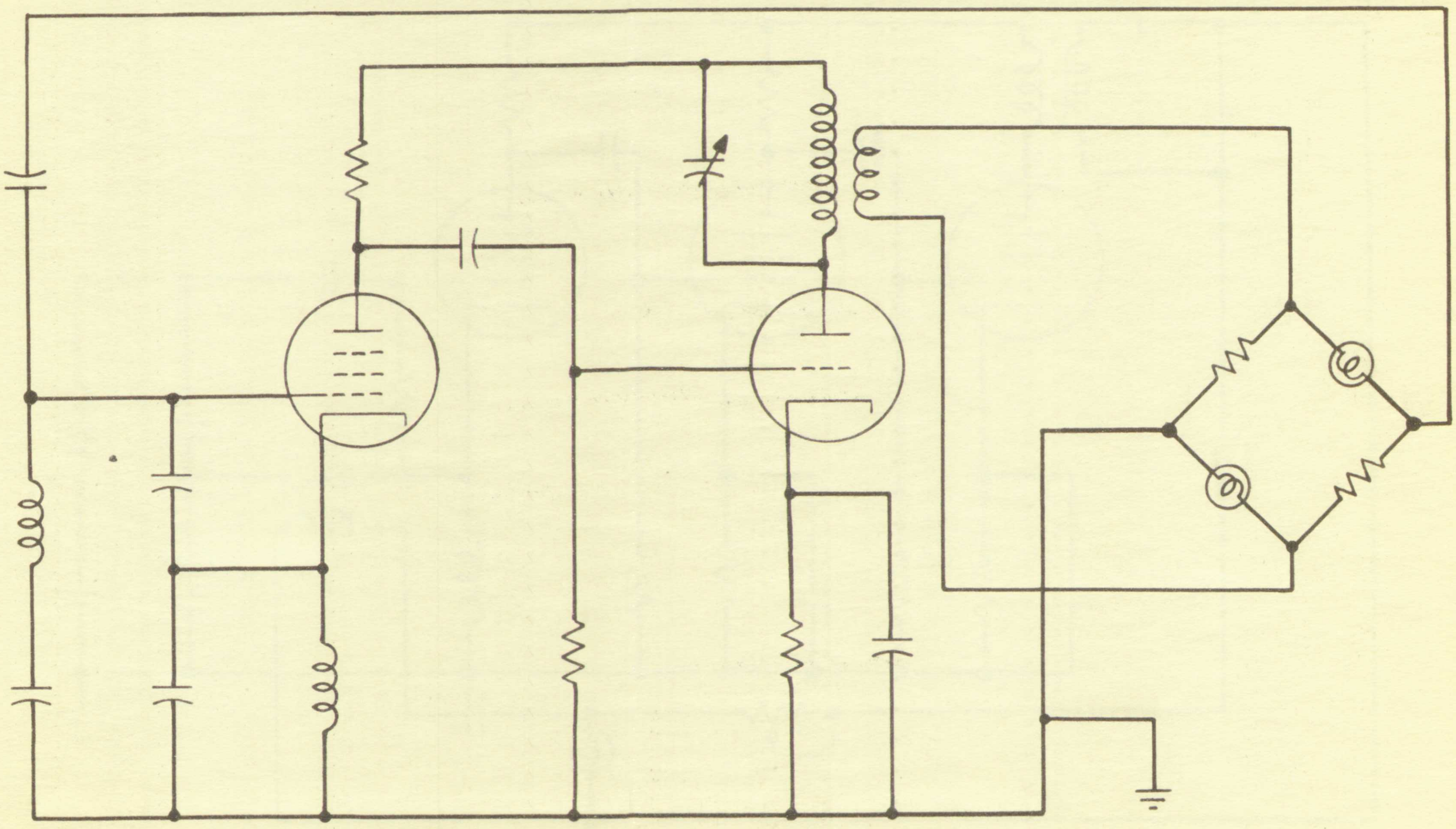

FIGURE 10 BRIDGE FEEDBACK CIRCUIT APPLIED TO GOURIET-CLAPP OSCILLATOR

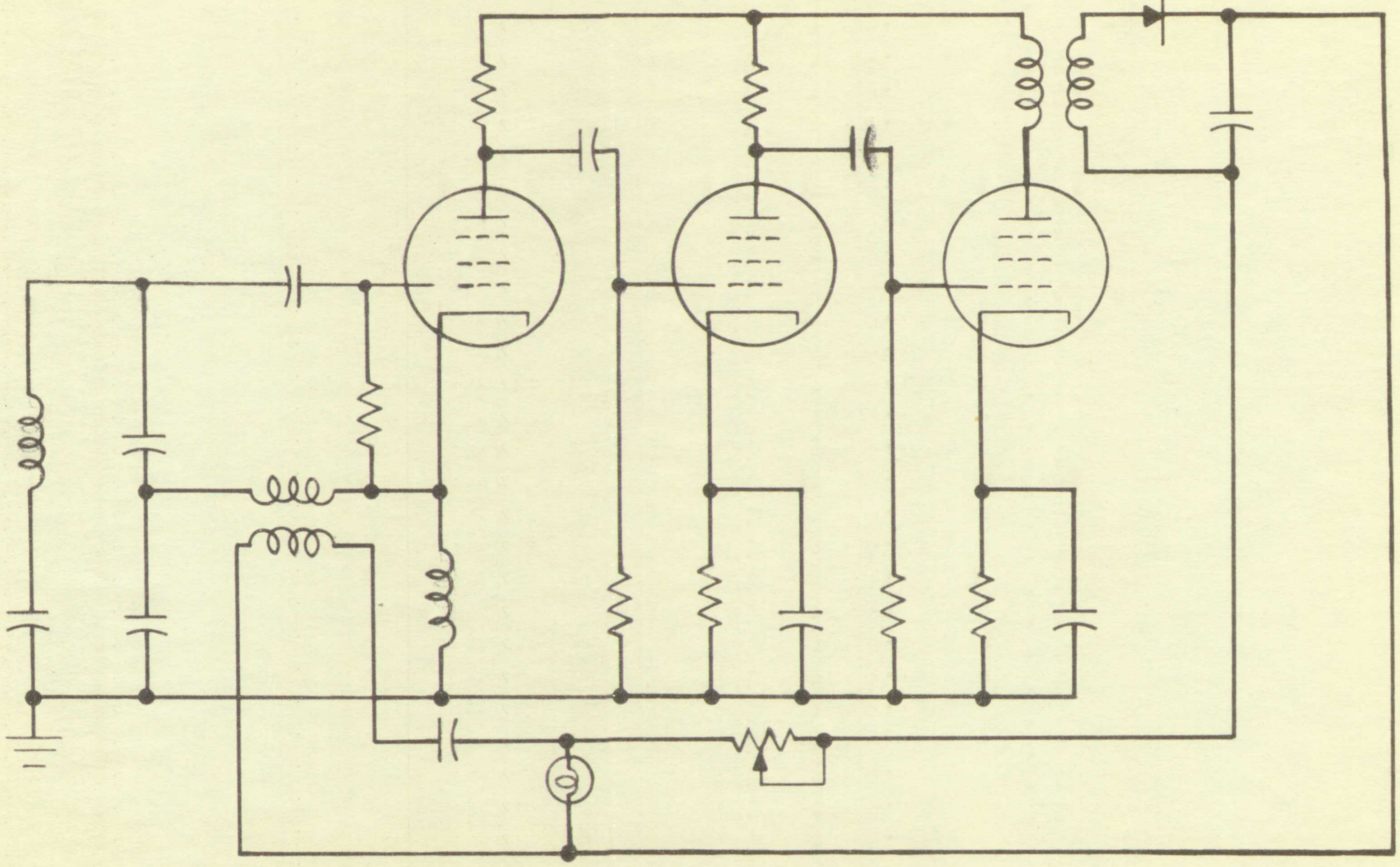

FIGURE 11 POSITIVE COEFFICIENT THERMISTOR CIRCUIT
APPLIED TO GOURIET-CLAPP OSCILLATOR

A portion of this direct current is fed to the lamp which is functioning as a varister.[18] Theoretically, only direct current is involved in the feedback loop and no phasing difficulties should be encountered.

If the signal increases in amplitude, a larger voltage is applied across the incandescent lamp; thereby causing its resistance to increase. The reflected resistance of the lamp then acts to divide down the voltage applied to the tank circuit. The reverse occurs if the signal is too small so that an equilibrium point is achieved by the proper setting of feedback parameters.

Unfortunately, coupling capacitance between primary and secondary of the transformers proved to be so large that in-phase components of the signal produced ruinous positive feedback that resulted in frequency instability. It was concluded that if feedback were to be achieved in a fairly simple manner, in the region of three megacycles, without the use of specially wound transformers and without sacrificing gain in the oscillator tube, a new circuit element or a new approach would have to be tried.

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[18] J. K. Clapp, "Frequency Stable LC Oscillators," Proc. I.R.E., 42:1295-1300, No. 8, (August, 1954).

What was needed seemed to be a circuit element which (a) could be used in the feedback path; (b) would have very low capacity between its input and output terminals; and (c) would serve to produce the desired negative feedback.

Negative coefficient thermistor feedback circuit. It appeared these requirements could possibly be met with an indirectly heated thermistor. Since no local source existed for such a device, a unit was fabricated in the laboratory. The filament from a Number 48 General Electric lamp was placed in physical, but not electrical, contact with a bead type thermistor. The two elements were held in position with a ceramic coating material and surrounded with an atmosphere of helium in a glass envelope.

This unit was placed in the circuit shown in Figure 12. The stray capacity between the heater and the thermistor measured 0.5 micromicrofarad, a low enough value to prevent positive feedback.

The indirectly heated thermistor shunted across the cathode choke serves to lower or raise the cathode impedance about a given operating point.

Thermistors have negative temperature coefficients. With the bead type used, this coefficient is quite large. For instance, at room temperature the bead resistance is roughly fifty thousand ohms. Sufficient heat to

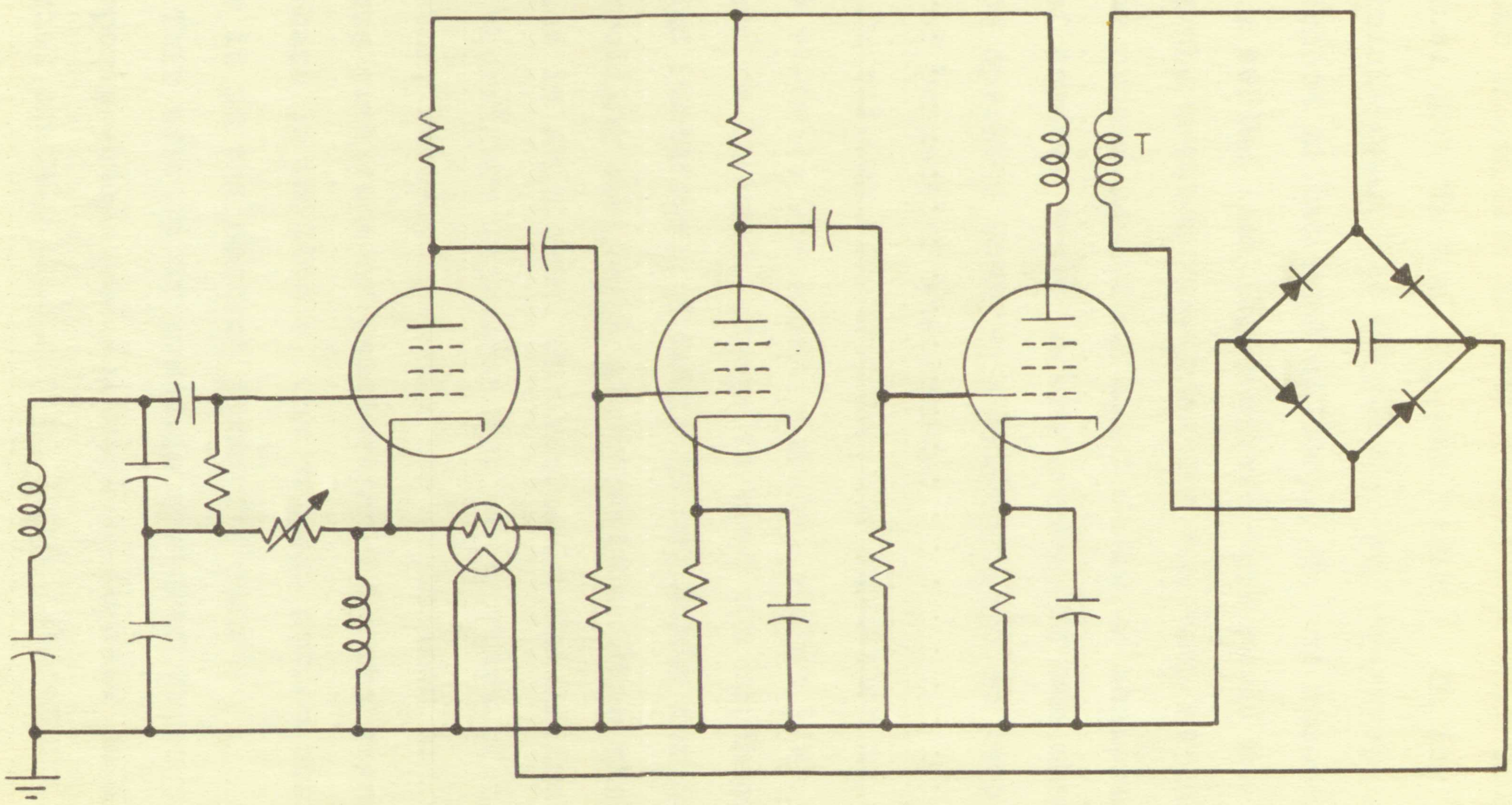

FIGURE 12 INDIRECTLY HEATED THERMISTOR APPLIED TO GOURIET-CLAPP OSCILLATOR FOR AMPLITUDE CONTROL

cause the thermistor to glow a dull red will bring its resistance down to the five ohm region. In the feedback circuit used, the thermistor was operated in the neighborhood of two hundred ohms. It was necessary to insert a series limiting resistor that could be varied between the cathode impedance and the tank circuit so that the proper operating point could be achieved. This, of course, would be unnecessary if the thermistor could be operated down to a hundred ohms or less without danger of burnout of the heater.

By raising and lowering the impedance in the cathode circuit, the signal applied to the tank circuit is raised or lowered. Thus, through the feedback amplifiers and rectifiers, a means is available for automatically controlling the level of operation. When the signal increases in amplitude, the heater of the indirectly heated thermistor increases the temperature of the thermistor; thereby lowering its resistance and attenuating the amplitude of oscillation. If the signal were to decrease in amplitude, the reverse action would then restore it to the correct operating point.

This circuit in practice appeared to be performing properly within the limitations imposed on it as a somewhat crudely constructed first laboratory model.

cause the [illegible]

radiation [illegible]

back directly [illegible]

neighborhood of [illegible]

induce a [illegible]

between [illegible]

that the [illegible]

This, of course, [illegible]

could be overcome [illegible]

danger of [illegible] the tube.

By [illegible]

cathode [illegible]

is raised or [illegible]

flows and [illegible]

ly controlling [illegible]

increase in [illegible]

heated [illegible]

thermionic [illegible]

ating the [illegible]

to decrease in [illegible]

restore it to the [illegible]

This [illegible]

ing [illegible]

a [illegible]

When a commercially constructed, indirectly heated, thermistor was obtained, it was placed in the circuit and enabled amplitude control down to fifteen millivolts between grid and cathode of the oscillator. This value, for all practical purposes, is so small that linear operation is obtained.

The following wiring diagrams, Figures 13, 14, and 15, present the resonator, the oscillator, and the feedback circuit in their final form. Two additional circuits are presented in Figures 16 and 17. These circuits are accessory circuits which convert the output signal of the oscillator from the three megacycle range down to a low range beginning at one kilocycle.

This enables the use of a frequency counter such as a Berkeley Instruments Company Model 5510 to count the frequency accurately. This unit has an upper counting limit of one million counts per second. The counter was chosen because a digital printer, manufactured by the same concern, will produce an automatic printout after each cycle of operation, when connected to its output.

[illegible]

thermistors [illegible]
and [illegible]
between [illegible]
for [illegible]
[illegible] is [illegible].

The [illegible]
and 15, produce [illegible]
feedback circuit [illegible]
circuits are [illegible]
circuits are [illegible]
signal of the [illegible]
down to a [illegible].

This [illegible]
as a [illegible]
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ing limits of [illegible]
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same concern, [illegible]
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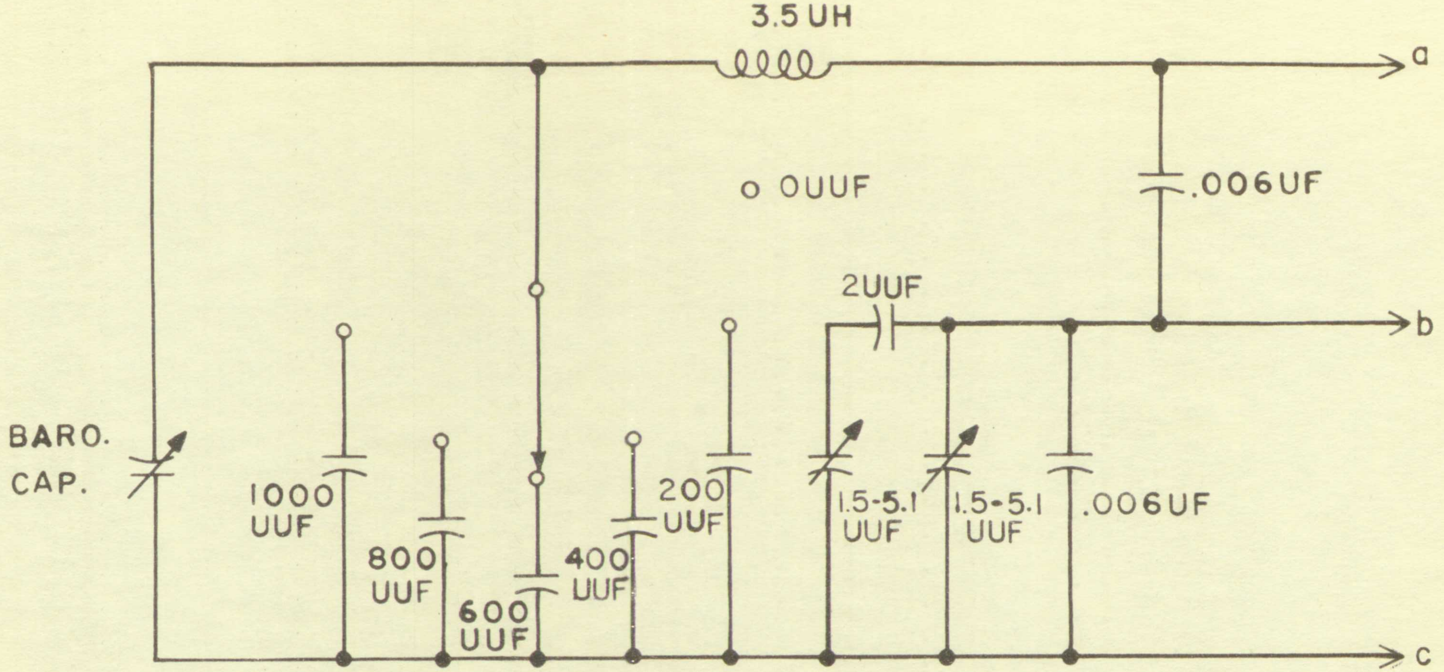

FIGURE 13 RESONATOR

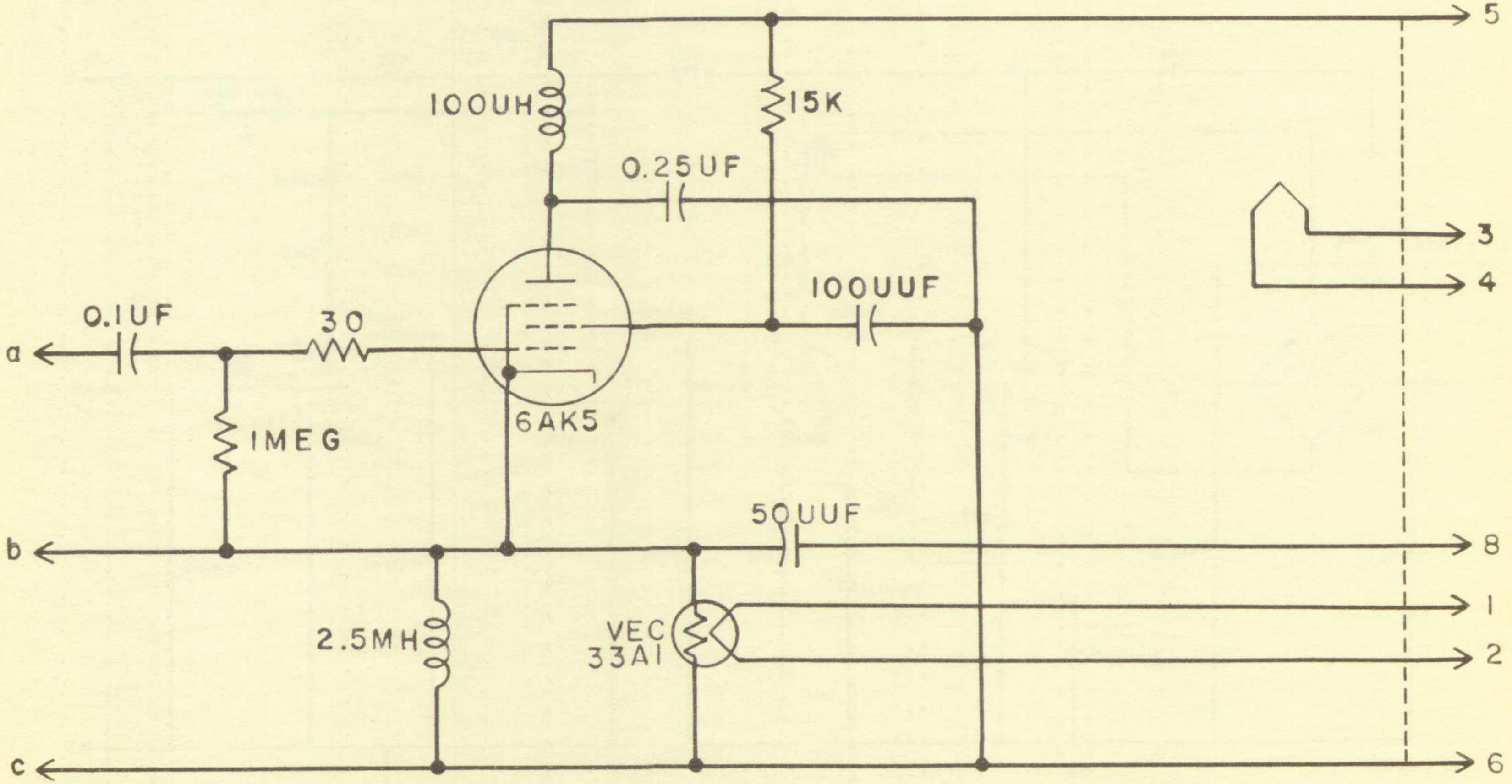

FIGURE 14 OSCILLATOR

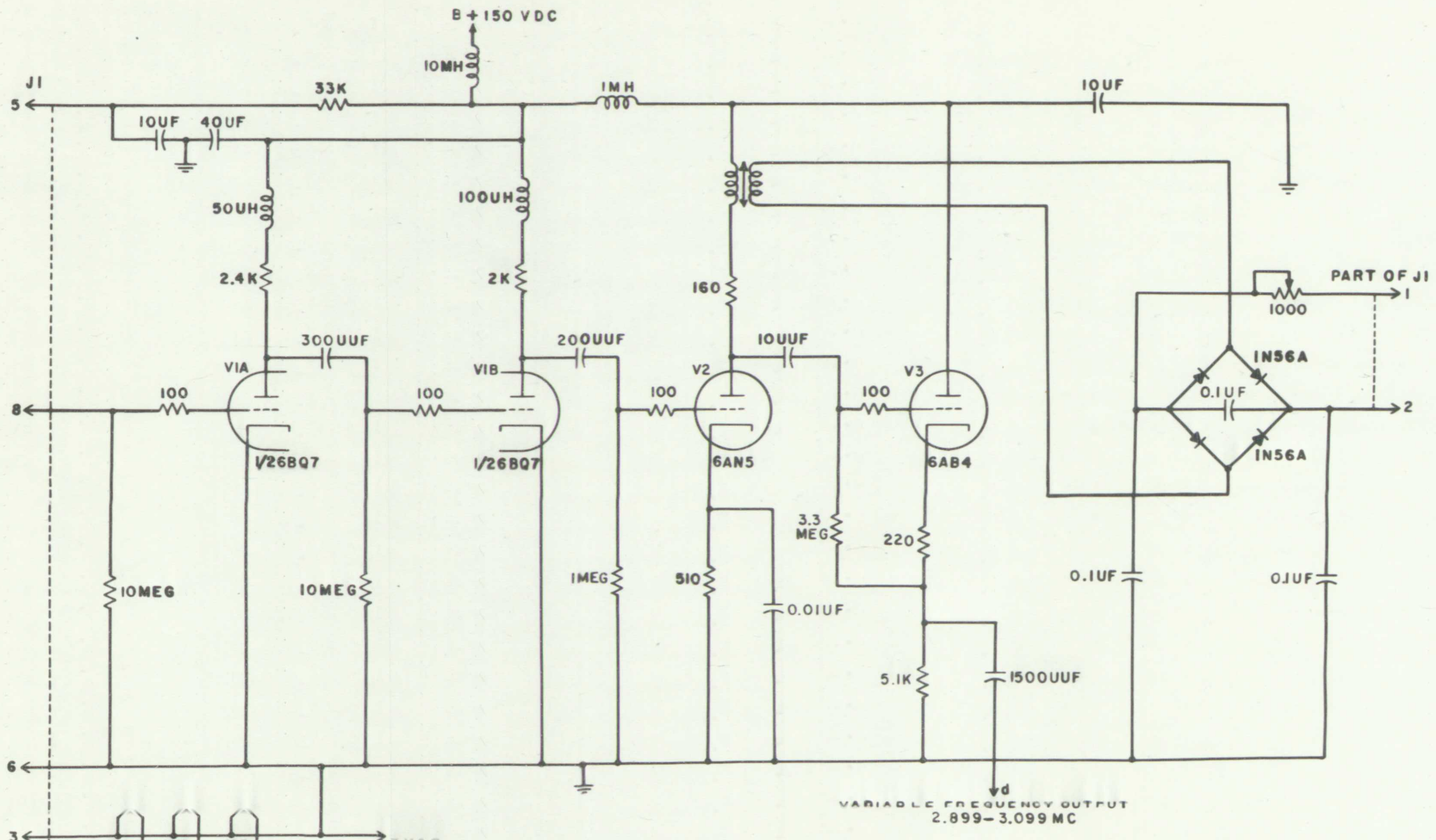

FIGURE 15 OSCILLATOR FEEDBACK CIRCUIT

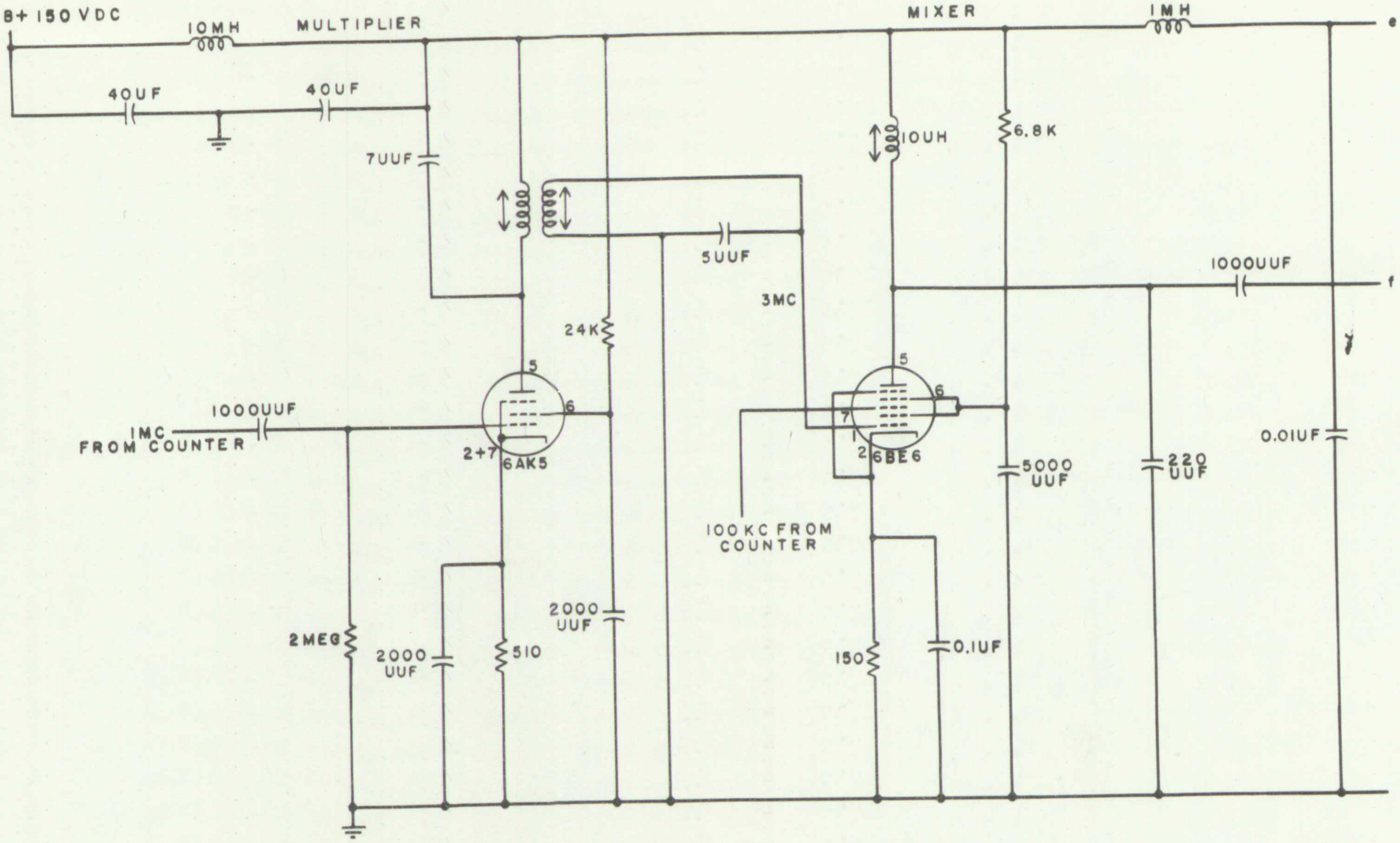

FIGURE 16 MULTIPLIER AND MIXER

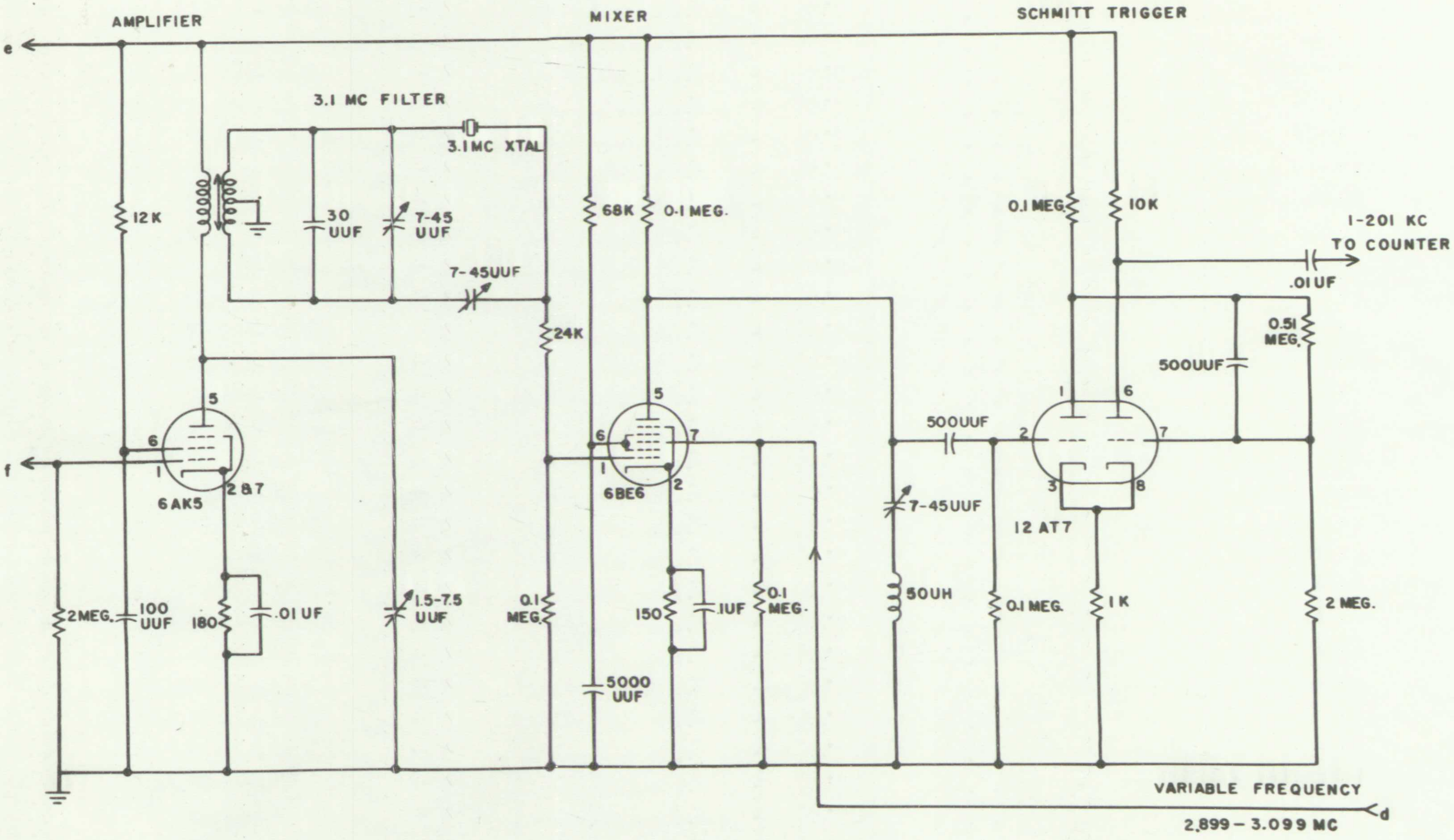

FIGURE 17 FILTER, MIXER AND OUTPUT CIRCUIT

CHAPTER III

THE FREQUENCY CONTROLLING CIRCUIT

The resonator. The resonator or frequency determining circuit is basically a parallel resonant LC combination where the quantity C or a fraction thereof is varied to produce a change in frequency of the oscillator.

Resonance may be defined in several ways, all of which are variations on the same theme.[19]

(1) The frequency at which $X_L = X_C$ or the resonant frequency of the same elements when operating in series resonance.

(2) The frequency at which the parallel impedance of the circuit has unity power factor.

(3) The frequency at which the parallel impedance of the circuit is a maximum.

From definitions number one or number two, it is obvious that for parallel resonance to occur, the reactance in the inductive branch must equal that in the capacitive branch or

$$X_L = X_C$$

Since $X_L = \omega L$ and $X_C = 1/\omega C$

$$\omega L = 1/\omega C$$

---

[19] Frederick E. Terman, Radio Engineers' Handbook, First Edition, Sec. 3, par. 2, pp. 143-144, (New York: McGraw-Hill Book Company, Inc.), 1943.

$$\omega^2 = 1/LC$$

where $\omega = 2\pi f_r$

and f_r is the center or resonant frequency.

So that:

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

Therefore, if L and C are constant, the resonant frequency is a constant and any variation in either L or C will cause a variation in the resonant frequency.

It is the purpose in this study to maintain the inductance of the resonator as constant as possible while variations in the capacitance determine the frequency of operation. This operation could, if desired, be worked the other way around or a variation of both used for any specific purpose.

It will now be necessary to determine the change in frequency for a small change in capacitance at any particular operating frequency. To determine this, the following derivation is useful.

<u>Derivation of frequency change for an incremental capacitance change at the frequency of operation.</u>

$$f_o = f_r$$

where f_o is defined as the frequency of operation or center frequency

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

where [illegible]

and [illegible]

hold [illegible]

Therefore, [illegible]

frequency is [illegible]

or C will change [illegible]

It [illegible]

inductance of the [illegible]

while varying [illegible]

frequency of operation [illegible]

sized, he [illegible]

both used for [illegible]

It [illegible]

in frequency [illegible]

particular [illegible]

following [illegible]

[illegible]

capacitance [illegible]

where [illegible]

as [illegible]

$$df_o = -\frac{dC}{4\pi C\sqrt{LC}}$$

$$\frac{df_o}{f_o} = -\frac{\frac{dC}{4\pi C\sqrt{LC}}}{\frac{1}{2\pi\sqrt{LC}}} = -\frac{dC}{2C}$$

$$\frac{df_o}{f_o} = -\frac{dC}{2C} \qquad (1)$$

Similarly, to determine a change in frequency for a given change in inductance:

$$\frac{df_o}{f_o} = -\frac{dL}{2L}$$

For the case of a tank circuit with two or more capacitors, thus:

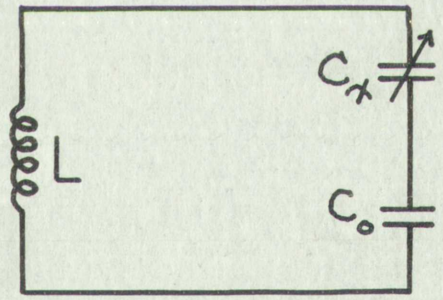

Figure 18 TWO CAPACITOR TANK CIRCUIT

If C_X changes and C_o remain fixed, then:

$$C_t = \frac{C_x C_o}{C_x + C_o}$$

Differentiating with respect to C_x gives:

$$\frac{d\,C_t}{d\,C_x} = \frac{(C_x + C_o)C_o - (C_x C_o)}{(C_x + C_o)^2}$$

$$\frac{d\ C_t}{d\ C_x} = \frac{C_xC_o + C_o^2 - C_xC_o}{(C_x + C_o)^2} = \frac{C_o^2}{(C_x + C_o)^2}$$

$$dC_t = \frac{C_o^2\ dC_x}{(C_x + C_o)^2}$$

Substituting C_t for C in equation (1) gives:

$$\frac{df_o}{f_o} = -\ ½\ \frac{\dfrac{C_o^2\ dC_x}{(C_x + C_o)^2}}{\dfrac{C_xC_o}{(C_x + C_o)}}$$

$$\frac{df_o}{f_o} = -\ ½\ \frac{C_o^2\ dC_x}{(C_x + C_o)\ (C_xC_o)}$$

$$\frac{df_o}{f_o} = -\ ½\ \frac{C_o\ dC_x}{C_x\ (C_x + C_o)} \qquad (2)$$

If, as in the Gouriet-Clapp Oscillator, the circuit consists of three capacitors:

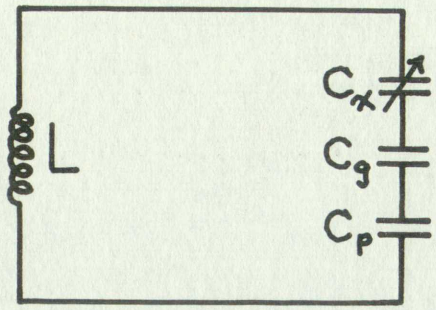

Figure 19 THREE CAPACITOR TANK CIRCUIT

where C_g and C_p are considered fixed in value, then by substituting

$$C_o = \frac{C_g C_p}{C_g + C_p}$$

in equation (2), a given change in frequency, df_o, may be determined for a given change in variable capacity, dC_x, at a given operating frequency, f_o.

At this point, some foresight is needed to decide how large an increment of frequency is desirable for a given increment of capacitance. This will in large part be determined by the stability of the oscillator since an incremental change in frequency, due to an incremental change in capacitance, must not be confused with a shift in oscillator frequency due to oscillator instability. Additional factors contributing to this decision are the complexity of the circuits associated with the oscillator and their corresponding increase in cost as the incremental change in frequency is increased.

It was felt that an increment of ten parts would be sufficient for a change of one hundredth of a micro-microfarad change in capacity. Calculations show that for this incremental frequency, an operating frequency of three megacycles is needed if $C_o = 3{,}000\ \mu\mu f$ and $C_x = 1{,}100\ \mu\mu f$.

The choice of C_x was fixed by the nature of the capacitive barometer. Measurements made previously indicated a total barometer capacitance range of approximately ten hundred micromicrofarads. This large capacitance spread is not practical from the circuitry standpoint. A change of ten hundred micromicrofarads would mean a change of about one megacycle in frequency. This large a frequency change produces a large change in Q of the inductor and thus a large change in oscillator gain. Since the feedback circuit is tuned over a fairly narrow frequency range, about three hundred kilocycles, it will not provide the necessary feedback signal to maintain a constant oscillator amplitude. A second limiting factor is that with increasing frequency, the effective gain of the oscillator tube decreases. This is the result of the gain-bandwidth product of the stage. For a stage of amplification, operating in a class A mode, there is a fixed gain bandwidth product which may be expressed by the equation:

$$GB = \frac{g_m'}{C_t}$$

where

G = gain of stage

B = bandwidth expressed as an angular frequency

g_m' = effective transconductance

C_t = total shunt capacitance across output of stage.

If the bandwidth is increased, the gain must drop to maintain this equality. Thus, oscillation will cease when the gain through the amplifier is insufficient to balance losses in the resonator. If, on the other hand, the frequency is decreased by about one megacycle, the incremental frequency resolution with changing capacity decreases.

In order to bypass these difficulties, the total capacitance variation is limited to approximately two hundred micromicrofarads. That is, the capacitance is maintained between the limits of ten and twelve hundred micromicrofarads by adding or subtracting external capacitance when the barometer exceeds these limits.

The value of C_o = 3,000 micromicrofarads is determined by the series combination of C_g and C_p. It was previously shown that the largest practical values should be used for these quantities in order to maintain

maximum stability. These values are, however, limited by the maximum obtainable gain of the oscillator tube and the losses in the resonator circuit. For all practical purposes, the capacitors are considered to be lossless. Therefore, the size of C_g and C_p are controlled by the Q of the inductor. The higher this Q, the larger may be the size of C_g and C_p.

Calculation of center operating frequency.

$$\frac{df_o}{f_o} = -\frac{1}{2}\,\frac{C_o\,(dC_x)}{C_x\,(C_x + C_o)}$$

$$\therefore\ f_o = \frac{-2(df_o)\,C_x\,(C_x + C_o)}{C_o\,(dC_x)} \qquad (3)$$

dC_x and df_o carry opposite signs so that the quantity on the right hand side of the equation is positive.

C_x = a center value of 1,100 micromicrofarads.

C_o = 3,000 micromicrofarads.

df_o = 10 cycles per second.

dC_x = 0.01 micromicrofarad.

$$f_o = \frac{(2)\,(10)\,(1{,}100)\,(1{,}100 + 3{,}000)\,(10^{-24})}{(3{,}000)\,(0.01)\,(10^{-24})}$$

maximum stability. Thus [illegible]

by the [illegible]

and [illegible]

purposes, the capacitive [illegible]

Therefore, the size of [illegible]

Q of the inductor. The [illegible]

the size of C_g and C_p.

Calculation of [illegible]

$$[illegible] = -2\frac{df_o}{f_o}$$

$$\therefore f_o = \frac{-2[illegible]}{[illegible]}$$

dC_x and df_o carry opposite [illegible]

on the right hand side of the [illegible]

C_x = a center value of [illegible]

C_o = 5,000 micro-[illegible]

df_o = 10 cycles per [illegible]

dC_x = 0.01 micro-[illegible]

$f_o = \frac{(2)(10)[illegible]}{(5,[illegible])}$

$$f_o = \frac{(2.2)\ (4.1)\ 10^6}{3}$$

$f_o = 3.0067 \times 10^6$ cycles per second.

Calculation of Inductance.

$$L = \frac{1}{4\pi^2\ f_o^2\ C_t}$$

$$C_t = \frac{(C_o)\ (C_x)}{C_o + C_x} = \frac{(3,000)\ (1,100)}{3,000 + 1,100}\ 10^{-12}$$

$C_t = 805 \times 10^{-12}$ farads

$$L = \frac{1}{(4)\ (9.86)\ (3.007)^2\ (805)}$$

$L = 3.49 \times 10^{-6}$ henries.

When $C_x = 1,000 \times 10^{-6}$ farads

$C_t = 750 \times 10^{-6}$ farads

$f = 3.11 \times 10^6$ cycles per second.

When $C_x = 1,200 \times 10^{-6}$ farads

$C_t = 857 \times 10^{-6}$ farads

$f = 2.91 \times 10^6$ cycles per second.

Therefore, the total frequency change is equal to 200,000 cycles per second.

Stability of Resonator Components.

Of major importance in the design of the resonator

circuit is the stability requirement of the components used.

It is a known fact that virtually every material has instabilities of one form or another. These instabilities take the basic form of variation in physical or electrical dimension and, in some cases, a manifestation of both. Changes in physical dimension take the form of thickness, length and width. Changes in electrical dimension assume the form of resistance, capacitance, and inductance. All these changes may occur because of changes in temperature, time, pressure, humidity, applied electrical potential or a combination thereof. For maximum stability, these factors must be minimized or so arranged as to cancel each other. It is by far a simpler procedure to use components in which instability effects are minimized than to attempt to balance out these effects by a choice of components. In many cases, the instability factors are nonlinear and cancellation, in all probability, could be achieved at only one operating point and time, if at all.

The resonator contains two basic elements of an electrical circuit, capacitance and inductance. Associated with these elements is series and parallel resistance. The wire leads connecting the elements and the wire used to form the inductor contain series resistance. Parallel resistance consists mainly of

circuit in the [illegible] used.

It is a [illegible] has instabilities [illegible] bilities take the [illegible] electrical dimensions [illegible] or both. Changes [illegible] thickness, length [illegible] dimension assume the [illegible] inductance. All these [illegible] changes in temperature, [illegible] electrical potential [illegible] maximum stability, [illegible] so arranged as to [illegible] simpler procedure [illegible] effects are minimized [illegible] these effects by a [illegible] the instability [illegible] in all probability, [illegible] point and time, it [illegible]

The resonator [illegible] electrical circuits, [illegible] associated with [illegible] resistance. The wire [illegible] the wire used to [illegible] distance. Tensional [illegible]

leakage through the capacitors and plays a minor role when high quality capacitors are used.

Capacitors. The desirable characteristics of a capacitor for this application are:

(1) Low temperature coefficient of capacitance.

(2) Low secular coefficient of capacitance.

(3) Low dissipation factor at the operating frequency.

(4) Convenient physical size.

(5) Minimum effect due to pressure change and humidity.

Because of the importance of number three and the lack of sufficient manufacturer literature on available capacitors, a test was made using a Boonton Q Meter, Type 260-A, to determine the relative merit of these units. The Q meter was operated at a frequency of approximately three megacycles. The inductor used to resonate the capacitors was locally fabricated. Its Q was about three hundred at three megacycles. Three samples of each type were tested with the average value of comparative Q listed in Table I. Items 3 and 6 seem to provide the best compromise for a fixed capacitor with low temperature coefficient and dissipation, and mica is known to exhibit excellent secular stability.[20]

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[20]William A. Edson, Vacuum Tube Oscillators, par. 6.5, p. 89, (New York: John Wiley and Sons, Inc., 1953).

leakage through [illegible]
when [illegible]
[illegible]
capacitor [illegible]
(1) [illegible]
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[illegible]

TABLE I

COMPARISON OF CAPACITORS WITH RESPECT TO COMPARATIVE Q AND TEMPERATURE COEFFICIENT OF CAPACITANCE

Company and Type	Capacitance (μfd)	Comparative Q	Temperature Coefficient of Capacitance (parts per million)
1. Condenser Products Co. Glassmike ASG 102-SM	0.001	37	1,000
2. Condenser Products Co. Glassmike LAG 501	0.001	257	-1,000
3. El Menco Co. Silvered mica	0.001	250	-20 to 100
4. Astron Corp. Molded paper tubular	0.001	25	nonlinear 700
5. El Menco Co. Mica padder	0.001	280	-200 to +200
6. Erie Corp. Silvered mica, button style	0.001	278	-20 to +100
7. Goodall Co. Nylon insulated tubular	0.001	50	nonlinear 3,500
8. Balco Corp. Synthetic insulated tubular (teflon or polystyrene)	0.001	230	75 to 100

TABLE I (continued)

COMPARISON OF CAPACITORS WITH RESPECT TO COMPARATIVE Q AND TEMPERATURE COEFFICIENT OF CAPACITANCE

Company and Type	Capacitance (μfd)	Comparative Q	Temperature Coefficient of Capacitance (parts per million)
9. General Radio Company Model 722N Variable air capacitor	set to 0.001	195	20
10. National Co. Variable air capacitor two STH-335 and one STH-300 in parallel	set to 0.0097	245	75 to 150

NOTE 1: Values of temperature coefficients are approximate and in many cases vary from unit to unit from the same manufacturer.

NOTE 2: The values of comparative Q for the variable capacitors may be greatly in error due to long leads to the Q meter which were necessary because of the physical dimensions of these units.

Item 5, Table I, page 47, appears attractive; but because of its physical construction, is subject to considerable drift.

It is necessary to employ some amount of variable capacitance in the resonator circuit to provide for compensation due to drift, and variation from precise value in the decade unit. Variable air dielectric capacitors are usually characterized by very low losses, and by having reproducible capacity settings.[21] Therefore, any high quality unit is satisfactory for this application as long as humidity is kept at low levels.

In general, high quality capacitors exhibit good secular and temperature characteristics with low hysterises effects and are easy to use in practice.

Inductors. The desirable characteristics of an inductor for this application are:

(1) Low temperature coefficient of inductance.

(2) Low secular coefficient of inductance.

(3) High Q at the operating frequency.

(4) Convenient physical size.

(5) Minimum effect due to pressure change and humidity.

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[21] Frederick E. Terman, Radio Engineers' Handbook First Edition, Sec. 2, par. 32, p. 119, (New York: McGraw-Hill Book Co., Inc., 1943).

Item 5, Table I, page [illegible]
of its crystal [illegible]
drift.

It is necessary [illegible]
capacitance in the [illegible]
temperature and [illegible]
value in the decade [illegible]
capacitors are usually [illegible]
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fore, any high quality [illegible]
application as long as [illegible]

In general, high quality [illegible]
hermetic and temperature [illegible]
hysteresis effects and [illegible]

Inductors. The [illegible]
inductor for this application [illegible]

(1) Low temperature [illegible]
(2) Low modulus [illegible]
(3) High Q [illegible]
(4) Convenient [illegible]
(5) Minimum [illegible]

humidity.

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[21] Frederick [illegible]
First Edition, Sec. [illegible]
McGraw-Hill Book Co. [illegible]

(6) Low hysteresis (good repeatability with temperature).

If the coil is tension wound on the former, items (1), (2), and (6) will be mainly a function of the core material when frequency effects are neglected. Therefore, this material should be carefully chosen to satisfy these conditions. Ceramic materials and some materials such as glass and quartz exhibit very good secular stability. Quartz and special ceramics and glasses have very low linear temperature coefficients of expansion; and their power factors, a measure of energy dissipation, are low in the one to ten megacycle range. Plastics in general have high power factors and poor stability. Table II lists in tabular form the materials considered for coil form use.

Of the materials listed, Stupalith A2417 seems to be a desirable choice because of its extremely low power factor and coefficient of linear expansion. Since its water absorption is high, precautions must be taken in high humidity climates. Quartz and good grade A lava are very good materials with quartz ranking first in choice over all materials when conditions of high humidity are encountered and the inductor cannot be sealed in a moisture proof container. There is the possibility of sealing the former surface pores with an impregnant

TABLE II

COMPARISON OF MATERIALS CONSIDERED FOR COIL FORM USE

Material	Dielectric Constant	Power Factor (@ 1 mc)	Coefficient of Linear Expansion (PPM/°C)	Water Absorption (% in 24 hours)
1. Pyrex Glass	4.5	0.2	3.2	0
2. Steatite	6.1	0.3	6 to 8	0.02
3. Fused Quartz	4.2	0.03	0.45	0
4. Titanium Zirconium Dioxides	40 to 60	0.05 to 0.1	6 to 7	0
5. Grade A Lava	5.3	0.01	2.9	2 to 3
6. Stupalith -A2417	5.56	0.005	0.063	21.5

of some kind. For the work at hand, grade A lava was used primarily because of its ready availability.

Investigation of the literature. Inductors, of all passive elements in an electrical circuit, are the most difficult components to predict. No one, to date, has been able to explain exactly why the temperature coefficient of inductors does not obey a sensible or logical set of laws. If a coil of wire which is free to expand in all directions is heated, its inductance theoretically should increase by a temperature coefficient at least equal to the temperature coefficient of linear expansion of the wire. That this is not true is well known and has been borne out by experiments; many investigators have tried to find experimentally and mathematically why this is so. Some worked with coils which were free to expand in all directions on high-expansion forms; some tried high-resistance conductors; others tried to bond the conductors to low-expansion forms. However, all results showed temperature coefficients of inductance that were at least twice the temperature coefficient of linear expansion for freely expanding coils, and unpredictable for bonded types.

The following discusses in chronological order the work done by various authorities in an effort to explain this discrepancy between theory and practice.

Moullin[22] calculated the temperature-inductance characteristic of a conventionally shaped coil in which axial expansion differed from radial expansion, but in which the shape of the turns remained circular. He pointed out that if the coil was free to expand radially, but held to a constant length, the temperature coefficient of inductance would be twice the coefficient of linear expansion of the conductor. This does not, however, explain why this is so for the coils which are free to expand in all directions, nor does it explain the high inductance coefficients found for coils firmly attached to low-expansion forms.

H. A. Thomas[23] reported the results of tests on a large number of single-layer coils and showed that the temperature coefficient of inductance was, as before, at least twice the conductor's coefficient of linear expansion. He attempted to explain the large coefficient by attributing it to self-capacitance changes and small changes in dimensions. He derived an expression for the temperature coefficient of inductance as follows:

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[22] E. B. Moullin, "The Temperature Coefficient of Inductance with Special Refeference to the Valve Oscillator," Proc. I.R.E., 23:65-84, (January, 1935).

[23] H. A. Thomas, "Stability of Inductance Coils for Radio Frequencies," I.E.E. Journal, 77:702-722, (November, 1935).

$$\gamma = (a + \omega^2 LC\,\delta) \,/\, (1 - \omega^2 LC)$$

where L = self inductance of coil

C = self capacitance of coil

a = temperature coefficient of linear expansion of form

δ = temperature coefficient of dielectric constant of form

$\omega = 2\pi f$ (where f = frequency of operation)

This assumed an absolutely tight bond between form and conductor. Thomas was the first investigator to mention the change in temperature coefficient of inductance with frequency. He built a coil using metallized turns on a Calit form, obtaining a good molecular contact between metal and form. At low frequencies and up to 75 per cent of the natural resonant frequency of the coil, good agreement was obtained between his equation and his results. At frequencies very low compared to the natural frequency of the coil, the coefficient of inductance is only slightly higher than the coefficient of linear expansion of the form. Later theory shows that this was caused by a fortuitous choice of a thin, flat conductor with large spacing between turns rather than by capacitance changes.

Janusz Groszkowski[24] attributed the excess in

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[24] Janusz Groszkowski, "The Temperature Coefficient of Inductance," Proc. I.R.E., 25:448-464, (April, 1937).

$\phi = (1 + \omega^2 LC$ [illegible] α

where L = coil inductance [illegible]

C = coil capacitance [illegible]

α = [illegible] coefficient of [illegible]
[illegible]

δ = [illegible] of dielectric
constant of [illegible]

ω = 2πf (where f = frequency of operation)

This assumes an absolutely [illegible] bond between form and conductor. Thomas was the first investigator to mention the change in temperature coefficients of inductance with frequency. He built a coil using metallized [illegible] on Cavit form, obtaining a good molecular contact between metal and form. At low frequencies not above 75 per cent of the natural resonant frequency of the coil, good agreement was obtained between the predicted and [illegible] results. At frequencies very low compared to the natural frequency of the coil, the coefficient of inductance is only slightly higher than the coefficient of linear expansion of the form. Later theory [illegible] that this was caused by a [illegible] effect of a thin, flat conductor with large [illegible] between turns rather than by capacitance changes.

James Greenwood[24] [illegible] is

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[24] James Greenwood, [illegible]
of Inductance," Proc. [illegible] (April, 1937).

actual temperature coefficient of inductance over the theoretical to eddy currents and skin effect in the conductor of the coil itself, and made measurements using constantan (which has temperature coefficients of resistivity and linear expansion of 8×10^{-6} and 17×10^{-6} per degree centigrade). Copper's coefficient of resistivity is $4,200 \times 10^{-6}$. He built a copper coil and measured a temperature coefficient of inductance of 45 parts per million. When an equal number of turns of constantan were added, the coefficient was found to be 47×10^{-6}, but when the same number of turns of copper were added the coefficient went up to 67×10^{-6}. He then made an identical coil of constantan and measured its inductance coefficient at 17×10^{-6} per degree centigrade, which is also its coefficient of expansion. When an equal number of copper turns were added, the coefficient increased to 28×10^{-6}, but when an equal number of constantan turns were added, the coefficient was found to be only 18×10^{-6}. From this, he concluded that eddy currents and skin effect have some bearing on the temperature coefficient of inductance because the constantan (which has almost no change in resistance with temperature) had inductance coefficients equal to its linear expansion coefficient, whereas the copper (which has a rapid change in resistance with temperature) had much higher inductance coefficients. Data was presented

also to show that the number of turns had to be kept small and the conductors large in order to minimize the change in coefficient with frequency.

Internal Inductance. E. B. Moullin[25] divided the inductance of a coil into two parts, external and internal. The external inductance is the portion of the total inductance which is directly related to the magnetic field outside the wire. It is not a function of frequency and has a temperature coefficient equivalent to the coefficient of linear expansion of the metal. The internal inductance is related to the magnetic field inside the wire. This portion is a function of frequency and has a temperature coefficient which is some function of the temperature coefficient of resistivity of the wire. While this internal inductance is approximately five per cent of the total for single-layer solenoids, it contributes greatly to the total temperature coefficient of inductance because it varies at a rate equal to the temperature coefficient of resistivity of the conductor metal. (Example: copper has a resistivity coefficient of 4,200 x 10^{-6}/degree centigrade.)

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[25] E. B. Moullin, "The Temperature Coefficient of Inductance for Use in a Valve Generator," Proc. I.R.E., 26:1385-1398, (November, 1938).

The internal inductance can be decreased by using conductors of hollow tubing with thin walls, or by use of thin, flat strips. However, this is accompanied by an increase in resistance.

This is borne out by Thomas[26,27] who found that coils which were wound with flat strips having thin cross-sections could be made to have inductance temperature coefficients almost independent of frequency over a wide range; but beyond this range, the coefficient rose rapidly with increasing frequency. He also found that the frequency at which the temperature coefficient of inductance started to rise could be increased by increasing the conductor spacing.

A. Block[28] reasoned that since the depth of penetration (and, therefore, the loss) varied according to the one-half power of the resistivity, the temperature coefficient of internal inductance for round conductors would be one-half the temperature coefficient of resistivity. He also showed that the temperature coefficient

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[26] H. A. Thomas, "The Dependence on Frequency of the Temperature Coefficient of Inductance of Coils," I.E.E. Journal, 84:101-112, (January, 1939).

[27] H. A. Thomas, "Electrical Stability of Tubular Inductance Coils with Deposited Conductors," I.E.E. Journal, 85:471-472, (May, 1940).

[28] A. Block, "Temperature Coefficient of Air-Cored Self-Inductances," Wireless Engineer, 21:359-367. (August, 1944).

The unusual [illegible]

conductors of [illegible]

of this. That [illegible]

an increase in [illegible]

This is [illegible]

coils which were [illegible]

occasions to [illegible]

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A. Bloch[28] [illegible]

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activity. He also [illegible]

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[26] A. [illegible] the Temperature Coefficient [illegible] I.R.E. Journal, [illegible]

[27] A. [illegible] Inductance Coils [illegible] Journal, 85:471-4[illegible]

[28] A. Bloch, [illegible] Self-Inductances," [illegible] (August, 19[illegible]).

of inductance caused by resistance changes for the whole coil was:

$$\alpha L = \delta/2Q$$

where δ = temperature coefficient of resistivity of metal in conductors, and Q = figure of merit for the coil.

To summarize the investigation into the temperature coefficient of inductance of a coil, the coefficient is a function of these nine things:

(1) frequency

(2) resistivity of the conductor

(3) temperature coefficient of resistivity of the conductor

(4) temperature coefficient of linear expansion of the conductor

(5) temperature coefficient of linear expansion of the form

(6) conductor shape

(7) form shape

(8) winding pitch

(9) number of turns.

To minimize the temperature coefficient of inductance, the number of turns must be kept small; and thin, wide conductors which are widely spaced and which have a low temperature coefficient of resistivity should be used. Unfortunately, all this tends toward a large coil with a low Q.

In an attempt to produce an optimum coil at the operating frequency, 1/8 inch copper tubing was used to form the coil. The coil diameter equalled 4 inches and was 2 inches long with a pitch of 3½ threads per inch. A Q of 400 was attained at 3 megacycles.

Fortunately, the physical size was convenient from a constructional standpoint. It proved relatively easy to shield the coil from electric and magnetic fields by placing it in the approximate center of a one-foot cubical aluminum container. The container was perforated with nine equally spaced 1 inch diameter holes in the top, bottom, and back surfaces for good air ventilation. Since the barometer enclosure was quite large, the volume of one cubic foot occupied by the container proved to be of no inconvenience.

CHAPTER IV

THEORETICAL ANALYSIS OF GOURIET-CLAPP OSCILLATOR

Minimum reactance of C_o. A simplified form of the oscillator is shown in Figure 20 (a). Since the cathode choke serves the purpose of a conducting path for direct currents and is in effect an infinite impedance at the frequency of operation, it has been omitted. In Figure 20 (b), the frequency determining elements have been removed and the capacitors C_g and C_p have been replaced by the generalized impedances Z_g and Z_p. Assuming the tube to have an infinite impedance (e.g., a perfect pentode) the current flowing through Z_p may be written as:

$$I_g + e_g g_m = I_p \qquad (1)$$

The voltage across Z_p is then:

$$Z_p (I_g + e_g g_m) = e_p \qquad (2)$$

and since

$$E_g = e_g + e_p \qquad (3)$$

then

$$E_g = Z_p (I_g + e_g g_m) + e_g = I_g Z_p + e_g (1 + g_m Z_p) \qquad (4)$$

and

$$e_g = I_g Z_g \qquad (5)$$

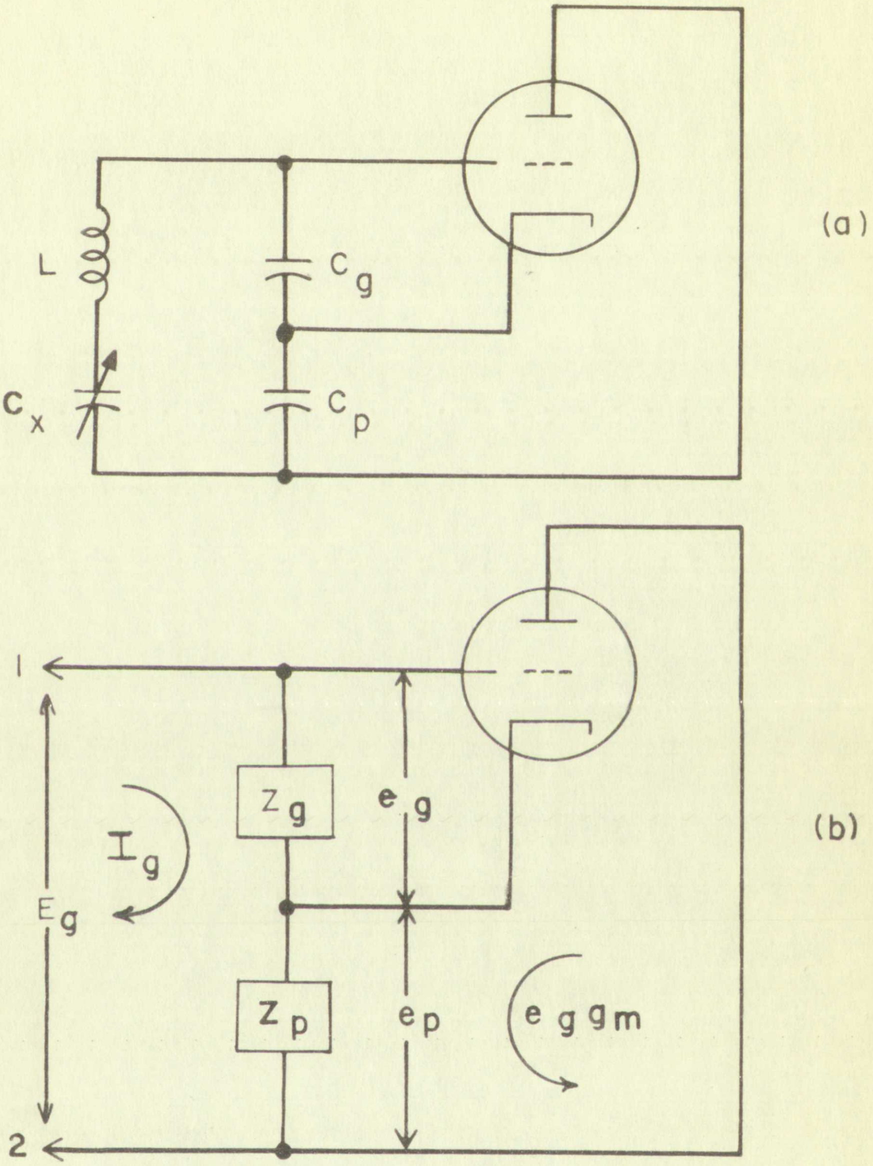

FIGURE 20 SIMPLIFIED FORM OF THE PRACTICAL CIRCUIT (a), AND THE GENERALIZED FORM OF ITS OSCILLATION MAINTAINING ELEMENTS (b)

therefore,

$$E_g = I_g Z_p + I_g Z_g (1 + Z_p g_m) \qquad (6)$$

dividing through by I_g then gives

$$\frac{E_g}{I_g} = Z_o = Z_p + Z_g + Z_p Z_g g_m \qquad (7)$$

which is the impedance looking into terminals 1 and 2.

From this, it will be seen then if Z_g and Z_p are pure reactances, jX_g and jX_p respectively, the impedance becomes

$$z_o = j (X_g + X_p) - g_m X_g X_p \qquad (8)$$

of which the real part will be negative, providing X_g and X_p are of the same sign.

Returning to the circuit of Figure 20 (b) in which Z_g and Z_p are the reactances C_g and C_p respectively, an input impedance is obtained which has a resistance component,

$$R_o = - \frac{g_m}{\omega^2 C_g C_p} \qquad (9)$$

in series with a capacitive reactance,

$$\frac{1}{\omega C_o} \quad \text{where } C_o = \frac{C_g C_p}{C_g + C_p} \qquad (10)$$

It will be noted that C_o is simply the series combination of the physically real capacitances C_g and C_p. With the

series LC element connected across this impedance, the condition of loop resonance which will determine the frequency of oscillation is given by

$$\omega L - 1/\omega C_x - 1/\omega C_o = 0 \qquad (11)$$

The energy equilibrium necessary for continuous oscillation will be satisfied when the losses in the resonator are balanced by the negative resistance R_o. Since these losses are practically all in the inductor, they may be represented as R_L, the resistance of the inductor so that

$$R_L = -R_o = \frac{g_m}{\omega^2 C_g C_p} \qquad (12)$$

By letting G equal the maximum value of transconductance that can be obtained from a tube under prescribed conditions, slightly more energy may be allowed for than is actually required to maintain oscillation so that the above equation may be written as

$$R_L \leq \frac{G}{\omega^2 C_g C_p} \qquad (13)$$

Now, it is desirable that the total capacitance C_o shall be as large as possible in order that the frequency of oscillation shall approximate closely the resonant frequency of the controlling elements L and C_x, but a limit to the maximum value is imposed by the above equation which states implicitly that for a given

frequency, unless the product $C_g C_p$ is sufficiently small to satisfy the equilibrium, the energy supplied will be insufficient to maintain the oscillation.

For a given product of C_g and C_p, the series capacitance C_o is a maximum when $C_g = C_p$, and by writing

$$C_g = C_p = 2C_o \qquad (14)$$

by substitution in (13)

$$\frac{1}{\omega C_o} \geq 2\sqrt{R_L/G} \qquad (15)$$

This equation is important, since it shows that for oscillation to be maintained, the minimum permissible reactance of C_o is a function only of the loss resistance of the frequency-controlling element and the tube transconductance.

<u>The effect on frequency of a change of Z_o</u>. Assuming that a modification to the impedance Z_o occurs, it is apparent that it can be accounted for completely in terms of a change of C_o, since the real part of Z_o must of necessity exactly equal the loss resistance R_L, which is of constant value over a wide frequency spectrum.

Thus, the merit of the circuit, from the point of view of frequency stability, is conveniently expressed

by the value of the differential df/dC_o which may be derived as follows.

Solving (11) for frequency:

$$\omega L = \frac{1}{\omega C_x} + \frac{1}{\omega C_o} \qquad (16)$$

$$\omega^2 = \frac{1}{LC_x}\,(1 + C_x/C_o) \qquad (17)$$

$$f = f_o\,(1 + C_x/C_o) \qquad (18)$$

where $f_o = \dfrac{1}{2\pi\sqrt{LC_x}}$

Differentiating (18) with respect to C_o gives

$$\frac{df}{dC_o} = -f_o \cdot \frac{C_x}{C_o^2} \cdot \frac{1}{2\sqrt{1 + C_x/C_o}} \qquad (19)$$

Since $\omega L \approx \dfrac{1}{\omega C_x}$

$$Q = \frac{\omega L}{R_L} = \frac{1}{\omega C_x R_L}$$

or $R_L = \dfrac{1}{\omega C_x Q}$ (20)

By substituting this value of R_L in (15) and taking the maximum permissible valve of C_o the following equation is obtained:

$$C_o = \frac{1}{2\omega}\sqrt{GQ\omega C_x}$$

Rearranging gives:

$$\frac{C_x}{C_o^2} = \frac{4\omega}{GQ}$$

Substituting in (19)

$$\frac{df}{dC_o} = - f_o \ \frac{2\omega}{GQ} \cdot \frac{1}{\sqrt{1 + C_x/C_o}} \qquad (21)$$

For small changes of the order of a few parts in a million, this may be written as

$$\frac{\Delta f}{f} = - \frac{4\pi f_o}{GQ} \cdot \frac{1}{\sqrt{1 + C_x/C_o}} \qquad (22)$$

where f is expressed in megacycles per second.

As a generalized expression of the stability, the equation in this form is very useful, since it is possible to obtain immediately the minimum value of the stability coefficient at any frequency, given the Q of the inductor and the maximum mutual conductance at which the tube can operate.

It is interesting to note from equation (22) that for circuits of similar Q, the coefficient is independent of the L/C ratio of the frequency controlling elements and also that its magnitude is directly proportional to frequency. The reason is bound up with the postulate

of a constant Q. Basically, though, since $Q = \omega L/R$, the frequency coefficient is essentially a function of the loss factor of the inductor and the transconductance of the tube. Since these two quantities are both fixed by physical considerations, increasing the frequency of operation to increase resolution is useless. It may be felt by some that the Q of the inductor increases with frequency, but in practice it has been found that this value remains constant over a considerable frequency spectrum and that when it does increase, the effective transconductance has decreased by an amount sufficient to offset the increased Q.

CHAPTER V

SUMMARY AND CONCLUSIONS

This final chapter contains a summary of the preceding chapters, and states the conclusions which were reached from both the experimental work and the theoretical analysis. Emphasis is placed upon the important results of the thesis and the results which are original. Mention is made of problematical aspects of the work that were not solved, but are listed for possible future investigation.

I. SUMMARY

A background of the problem was presented stating why it was conceived and how it was approached. It was shown that of the possible ways of producing an accurate reading on a barometric mercury column the use of a capacitive type transducer seemed to offer the simplest and most reliable means. It was then shown that an oscillator whose frequency could be varied by the transducer would be of greatest advantage in producing a digital print-out so that in the hands of an unskilled operator, pressures accurate to 0.01 millimeter of mercury could be obtained.

The problem was then presented of constructing a variable oscillator with sufficient stability to meet the requirements of accuracy and high resolution. The choice of oscillators was narrowed down to a variety that used a combination of inductance and capacitance as the frequency controlling elements.

The conclusion was reached that of these, an oscillator developed independently by Clapp in America and Gouriet in England would satisfy the over-all requirements. It was further shown that this oscillator is an exact analogy to the well known Pierce crystal oscillator.

The major factors contributing to frequency instabilities were then enumerated. These factors were shown to be:

1. Resonator Q
2. Temperature effects
3. Changing supply voltage
4. Harmonic generation
5. Photoelectric effects
6. Vibration

Laboratory work was carried on in an endeavor to minimize or in some cases eliminate these sources of instability. Emphasis was placed upon the development

of a somewhat novel negative feedback circuit to minimize harmonic generation. Reasons were then given for the superiority of this circuit over presently existing schemes for producing a similar result.

Exact circuit diagrams were presented for the oscillator, its negative feedback circuit, and associated circuitry for developing a beat signal that covered a frequency spectrum from 1,000 to 201,000 cycles per second, so that a relatively inexpensive and simple frequency counter could be used to present the read-out.

A study was then made of the components that form the resonator of the oscillator. The study was divided into two parts, the capacitors and the inductor. It was shown that the higher quality of capacitor readily available from commercial channels is adequate from the standpoint of low temperature coefficient and long term capacitance stability. The inductor, however, was a more difficult problem in that the desirable features on the one hand produced undesirable features on the other. The inductor, therefore, was a compromise. What was used in practice was an optimized coil that seemed to provide the best solution without the necessity of creating a separate research project. The inductor was fabricated by winding 1/8 inch copper tubing on a

lava former at 140 degrees Fahrenheit so that upon cooling to ambient temperature, the turns were under tension.

The resonator was placed in an aluminum container of one cubic foot volume so that external magnetic and electric fields would be minimized. The container was perforated so that air currents from the temperature controlling oven could circulate freely and maintain the resonator to within 0.01 degree centigrade about the operating temperature. Since the mercurial manometer was to be controlled to the same temperature limits, no inconvenience was experienced in placing the resonator in the same oven used to control the manometer temperature.

A theoretical analysis was presented for the Gouriet-Clapp oscillator. The analysis is sufficiently broad in scope to produce the necessary design equations for any given set of conditions when building an oscillator of this type. That is, for a given tube transconductance, frequency of operation, and inductor Q the proper value of C_o may be calculated to produce and maintain oscillation. The analysis was carried further to show that the stability coefficient is implicitly a function of tube transconductance and inductor Q. It

is therefore evident that the higher these two quantities, the more stable will be the oscillator.

II. CONCLUSIONS

As a result of the theoretical and experimental work, it is concluded that:

(1) The Gouriet-Clapp oscillator described in this paper performs satisfactorily for use as a variable oscillator in conjunction with the capacitive pressure sensing element.

(2) It exhibits a short-term stability of one part in three million when the resonator temperature is held to within 0.01 degree centigrade at an ambient temperature of about 26 degrees centigrade.

(3) Since the drift of one part per hour represents an error of 0.001 millimeter of mercury, little error is introduced by the oscillator if its frequency is calibrated once every hour or so when in use.

(4) The design equations presented in Chapter III and Chapter IV should enable an interested party to adequately design the oscillator for any particular application where an oscillator of this type may be desirable. It should be noted that this oscillator may be built with center frequencies from the audio range to well over one hundred megacycles if properly constructed.

III. RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

It should be stated that the oscillator feedback circuit is somewhat complicated and as such may be unreliable as to component failure. Although extensive work was done in connection with feedback circuits, it is felt by this investigator that further work and study on the subject could possibly produce a simpler circuit involving fewer tubes and crystal rectifiers which would achieve the same end as to performance and result in greater reliability. Beside the benefits just mentioned, two additional benefits to be gained would be less current drain on the power supply and a lower priced unit.

Much work remains in the field of resonator development. This is the weakest link in the oscillator. Improvement of oscillator stability is mainly a function of improved resonator stability since the circuit possesses a stability inherently greater than that achieved by the investigator. This has been borne out in practice by the Pierce oscillator which has been made to operate, with the use of a carefully ground crystal, to stabilities of the order of one part per billion per day. The major source of drift in the resonator is caused by the inductor. Although this component has been studied by many workers in the field of electronics,

no one has produced or approximated an ideal unit for an application similar to the one discussed in this paper. It may be possible that a completely unconventional inductor would provide a solution to the problem.

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