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DESIGN, ANALYSIS AND TESTING
OF A GENERATOR OF STANDARD
FREQUENCIES

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DESIGN, ANALYSIS AND TESTING
OF A GENERATOR OF STANDARD FREQUENCIES

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CHAPTER I

STANDARDS OF FREQUENCY

1.1 Introductory Discussion

In the universe, as we know it, there have been observed many phenomena which have a recognized periodicity or standard frequency. Several of these have come into prominence through their continued use as fundamental constants.

As is well known, our fundamental standard of frequency is the period of the earth's rotation about its axis. This period is, to a very high degree, constant. Obviously, this period could not be exactly a constant due to the action of the lunar and solar gravitational forces, to name but a few.

The mean, or average, period of rotation can be very accurately measured by astronomical methods and is known as "one cycle per day". Almost all standards of frequency are referred to this fundamental source for calibration purposes.

1.2 Standards of Frequency - Classification

A frequency standard may be classified as either a primary or secondary standard.

A primary standard of frequency is an instrument capable of generating a highly accurate, constant frequency which is regularly checked against the earth's rotation. Usually, this frequency is generated

by a quartz crystal which is used to regulate the time shown on a clock and which also activates harmonic and sub-harmonic generators thus providing a series of highly accurate known frequencies. Experimentation is also being done using atomic and molecular spectral lines as standard frequency sources.

A secondary standard of frequency is the frequency of a stable oscillator that is regularly checked against the frequency of a primary standard.

1.3 Methods of Frequency Measurement

There are several well known methods of frequency measurement which are currently in use, of which an outline follows.

By the use of suitable circuits, harmonic multiples of the standard frequency may be obtained as was indicated above. Therefore, known frequencies may be obtained in the region of practically any unknown frequency, and the problem reduces to one of interpolation.

(a) Direct - Beating methods

In these methods voltages of the unknown frequency and of the known frequency are impressed upon the input of a detector and the value of the resulting difference beat-frequency is determined by methods such as the following:

1. Matching the beat frequency with that of an adjustable, calibrated interpolation oscillator.
2. Measuring the difference beat frequency on a frequency bridge or on a cathode ray tube by means of Lissajous patterns.
3. Measuring the difference beat-frequency on a pulse or frequency counter or counter circuit.
4. Measuring the difference beat-frequency on a direct reading frequency meter.

(b) Direct - Interpolation method

The frequency of an interpolation oscillator of suitable range is zero beat against the unknown frequency and the adjacent harmonics of the standard frequency in turn, with the resulting information yielding the value of the unknown frequency.

(c) Harmonic - Interpolation method

This method consists of beating together the unknown frequency and a harmonic multiple of the interpolation oscillator's frequency or, alternately, of beating together the interpolation oscillator's frequency and a harmonic sub-multiple of the unknown frequency which leads to the value of the unknown frequency.

(d) Subtraction method

This method consists of combining the unknown frequency with a suitable known frequency and ob-

taining a resultant which has one less digit than the original. Then another frequency is combined with the above resultant and a second resultant is obtained which differs from the original by two digits. This process is repeated until the resulting frequency difference is negligible.

(e) Direct measurement method

This method consists of directly beating the unknown against a calibrated variable frequency oscillator until a null point is obtained. When this is obtained the frequency of the oscillator is the same as that of the unknown and thus the unknown frequency is measured.

There are other methods, examples of which are lecher wire measurements, direct reading frequency meters, etc.

This thesis is concerned with the construction of a standard frequency generator which may be used as a frequency source for frequency measurement purposes.

C H A P T E R I I

THE OSCILLATOR

2.1 General Discussion

In any device for the precision measurement of frequency the most critical feature is, of course, the frequency controlling device. In frequency standards this section is the oscillator and any oscillator controlled harmonic or sub-harmonic generators. Investigations carried out by numerous researchers over the last score or more years have indicated that, of the several types of known oscillators, the piezo-electric crystal oscillator is the best.

The crystal oscillator has been found to be the most successful master oscillator. Frequencies harmonically related to a submultiple of the base frequency are best generated by crystal controlled oscillators.

2.2 Crystal Oscillators

Oscillators employing crystals may be classified in a number of ways. One classification is based upon whether or not the circuit without the crystal is in itself an oscillator.

If the circuit, when the crystal is not actively included in it, is not inherently capable of sustained oscillation; then it is termed a "crystal"

oscillator.

If the circuit is capable of sustained oscillations when the crystal is not actively included in the circuit, although not necessarily at the crystal's resonant frequency, then it is termed a "crystal controlled" oscillator.

2.3 Negative Resistance

Oscillators are in general classified as negative resistance type oscillators. This negative resistance is in general due to several circuit features: Positive feed-back which is introduced to balance the circuit losses, and the vacuum tube which over a part of its operational range is inherently a negative resistance element.

The negative resistance is a necessity since the alternating-current resonant-frequency ohmic losses must be zero. If these losses were not identically zero, the amplitude of the oscillation would exponentially decrease until its value be less than a usable minimum.

2.4 Conditions for Oscillation

The analysis of the oscillator is based upon the fact that the circuit may be considered to consist of a anti-resonant RLC combination in parallel with the negative resistance element. This is justified because

the crystal itself performs as if it were a high-Q LC anti-resonant circuit. Numerous investigators have empirically developed its equivalent circuit, and the operation of crystal oscillators may be determined by using the established empirical relationships. The analysis is performed exactly the same as that for an LC oscillator circuit.

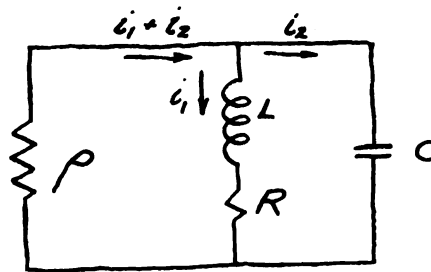


Fig. 2.1 Equivalent Circuit.

By using the Kirchhoff laws we may write

$$\rho(i_1 + i_2) + L \frac{di_1}{dt} + Ri_1 = 0$$

$$L \frac{di_1}{dt} + Ri_1 + \frac{1}{C} \int i_2 dt = 0$$

where ρ , algebraically positive, is the negative resistance element.

By methods of differential equations we may eliminate one of the unknown currents and obtain a single equation in one unknown

$$\rho LC \frac{d^2 i_1}{dt^2} + (\rho RC + L) \frac{di_1}{dt} + (\rho + R)i_1 = 0$$

or after dividing by ρLC

$$\frac{d^2 i_i}{dt^2} + \left(\frac{R}{L} + \frac{1}{\rho C} \right) \frac{di_i}{dt} + \left(\frac{1}{LC} + \frac{R}{\rho LC} \right) i_i = 0$$

This resultant expression in one unknown is a standard form whose solution is known, which is

$$i_i = A e^{-\frac{1}{2} \left(\frac{R}{L} + \frac{1}{\rho C} \right) t} \sin \omega t$$

where

$$\omega = \sqrt{\frac{R + \rho}{\rho} \frac{1}{LC} - \frac{1}{4} \left(\frac{1}{\rho C} + \frac{R}{L} \right)^2}$$

Thus it is seen that if ω is a real quantity then the determination of the type of oscillation, i.e., constant, increasing or decreasing with time, is explicitly dependent upon the magnitude of $|\rho|$.

Reich⁽¹⁾ has summarized the results of these expressions as follows:

A. Sinusoidal oscillation may occur if ω is real, i.e. if

$$|\rho| > \frac{L}{RC - 2\sqrt{LC}}$$

1. The amplitude of oscillation decreases with time if

$$\frac{R}{L} + \frac{1}{\rho C} > 0$$

(1) Reich, H. J., Theory and Applications of Electron Tubes, McGraw-Hill, 1944, 2nd Edition, p. 376

2. The amplitude is constant if

$$|\rho| = \frac{L}{RC}$$

3. The amplitude increases with time if

$$|\rho| < \frac{L}{RC}$$

B. The current is exponential in form if is imaginary, i.e., if

$$|\rho| < \frac{L}{RC - 2\sqrt{LC}}$$

1. Sustained oscillation occurs if

$$|\rho| \leq \frac{L}{RC}$$

- a. The current wave is continuous, but non-sinusoidal if $|\rho| > R$.
- b. Triggering occurs and the wave has discontinuities, i.e., relaxation oscillation takes place, if $|\rho| < R$.

2. The current is an exponential pulse if

$$|\rho| > \frac{L}{RC} \text{ and } |\rho| \geq R.$$

2.5 Stability

In any source of constant frequency output the stability of the oscillator section is of major importance. If the instantaneous or operating frequency should be grossly affected by incremental variations in the operating conditions, the utility of the instrument

would be drastically reduced.

The frequency stability of the oscillator has been found to be dependent upon several factors:

- (a) Mechanical arrangement of the parts,
- (b) Circuit parameters,
- (c) Tube parameters,
- (d) Operating conditions, i.e., temperature, vibration, etc.

2.6 Stabilization

By careful consideration of the mechanical arrangement, i.e., using electrically and thermionically stable parts, rigid construction, thermostatically controlled crystal housing, and by using voltage and current regulation, most of the difficulties in items (a) and (d) above can be effectively eliminated. The lines of research to reduce the effects of the tube and circuit parameter variations upon frequency stability have proceeded in several directions, an outline of which follows:

- (a) Proper choice of electrical parameters of the oscillatory circuit, i.e.,
 - (1) Resistance stabilization
 - (2) Capacitance or inductance stabilization
- (b) Use of selective filters as the oscillatory circuit

(c) Elimination of harmonic content by
means of tuned filters

One of the simplest ways of improving the frequency stability of an oscillator is by resistive stabilization, which consists of the addition of a high resistance between the plate and the oscillatory circuit. The purpose of this is to make the total effective resistance in the plate circuit so high that variations in the dynamic plate resistance will have little effect upon the oscillatory circuit.

Llewellyn⁽²⁾ has developed a more general type of stabilization. By deriving the analytical expression of the requirements of oscillation for a general type circuit he found that by using capacitance or inductance in series with the grid or plate of the oscillator, or both, complete independence of oscillation frequency from variation in tube parameters resulted.

A number of investigators have shown that frequency variation and harmonic control are interdependent. The factors that ensure low harmonic content, such as a linear operating characteristic and small amplitude, therefore also tend to improve

(2) Llewellyn, F. B., Constant Frequency Oscillators, Proc. I.R.E., Vol. 19, p. 2063, Dec., 1931

frequency stability. Stability can also be improved by the use of series filter sections tuned to the harmonic frequencies, shunted across the tube circuit.

2.7 Non-Crystal Negative-Resistance Oscillators

Chakravarti⁽³⁾ has analyzed and classified negative resistance oscillators into three classes as follows:

- A. DYNATRON TYPE, in which the internal resistance of a triode or screen-grid tube under secondary emission condition has been used to obtain negative resistance.
- B. TRANSITRON TYPE, in which a five element or double-grid tube employing negative transconductance has been used.
- C. FEED-BACK or REGENERATIVE TYPE, in which the input and the output terminals of a one-way amplifier are connected in series or parallel.

2.8 The Dynatron Oscillator

In a screen-grid tube if the electrode is operated at a higher voltage than the plate, and there is sufficient secondary emission from the plate, there

(3) Chakravarti, S. P., On the Nature of Negative Resistance and Negative Resistance Sections, Phil. Mag., Vol. 30, p. 294

is a range of plate voltages over which the net resultant plate current will decrease with increasing plate current.

The negative resistance results from the fact that while the number of primary electrons that the plate receives is independent of the plate voltage, the number of secondary electrons produced at the plate increases with increasing plate voltage.

It is seen that the magnitude of the negative resistance can be controlled by varying the control-grid potential. Fig. 2.2 shows the schematic circuit diagram of the dynatron oscillator.

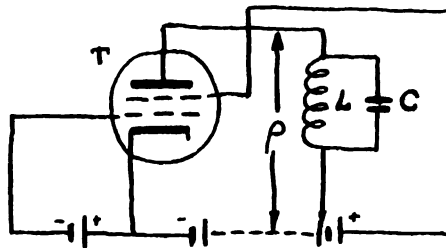


Fig. 2.2 Dynatron-oscillator Circuit

This type of oscillator has one general type of disadvantage. This is its dependence upon secondary emission. Secondary emission changes with use of the tube and large differences have been observed in the shapes of the characteristics of individual tubes of the same type. Since for stable operation the influence of tube parameter variations should

be as small as possible this type of oscillator is effectively eliminated.

2.9 The Transitron Oscillator

The transitron oscillator is also known as the retarding field or negative-transconductance oscillator⁽⁴⁾.

The pentode is connected as indicated in Fig. 2.3 and the potentials so adjusted that there is a virtual cathode between the screen and the suppressor. Under these conditions a fraction of the space current drawn from the cathode is returned back toward the cathode, to be ultimately collected by the screen.

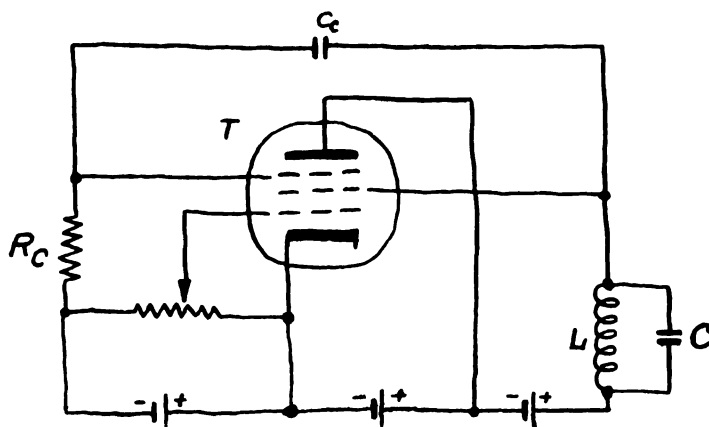


Fig. 2.3 Transitron Oscillator.

(4) Reich, H. J., Theory and Application of Electron Tubes, McGraw Hill, 1944, 2nd Edition, p. 381

In the transitron oscillator, and in the circuits derived from it, both the suppressor and screen voltages are permitted to have a.c. components.

Another distinguishing feature of this type circuit is that neither the anode nor the first grid plays a part in the a.c. circuits. These electrodes are maintained at pure direct current potentials although in many practical instances the synchronizing voltage is applied through the first or control grid.

Instead of using the first grid voltage to control the anode current, as in a triode, we have here the novel device of using the suppressor voltage to control the screen current. Thus in a transitron-connected pentode-amplifier the load is connected in the screen circuit, and the input voltage is connected in the suppressor circuit.

The variations of the anode voltage of the pentode have very little effect on the total space current. This is because the screen grid effectively screens the cathode region from the influence of the anode-voltage.

With the suppressor connected to the cathode in the orthodox way, the proportion of the space current going to the anode increases with anode-voltage until finally nearly the whole space current becomes anode-current. If now the suppressor voltage is made

increasingly negative, the repulsion of electrons by this electrode increases, and the proportion of the space current which reaches the anode is reduced. The proportion going to the screen is thus increased and it follows that making the suppressor voltage negative increases the screen current.

Contrast this with the behavior of a triode, where making the control-grid voltage negative decreases the controlled current. Herein lies the key to the properties of the transitron, positive feedback may be applied simply by R-C coupling the output to the input.

If, in Fig. 2.4, C_0 and R_0 are large enough so that a change in voltage of the screen grid G_2 is accompanied by a practically equal change in voltage of the suppressor grid G_3 , the action is mathematically as follows:

$$\Delta i_{c2} = \frac{\Delta e_{c2}}{r_{g2}} + \Delta e_{c3} G_{32} = \Delta e_{c2} \left(\frac{1}{r_{g2}} + G_{32} \right)$$

where Δi_{c2} is the change in the current of the screen grid G_2 ,

Δe_{c2} is the change in the voltage of the screen grid G_2 ,

r_{g2} is the screen grid resistance,

Δe_{c3} is the change in the voltage of the suppressor grid G_3 , and

G_{32} is the mutual conductance between G_2 and G_3 .

Since G_{32} is negative, it follows that, if the magnitude of G_{32} exceeds the magnitude of $1/r_{g2}$, an increase of screen voltage is accompanied by a decrease of screen current.

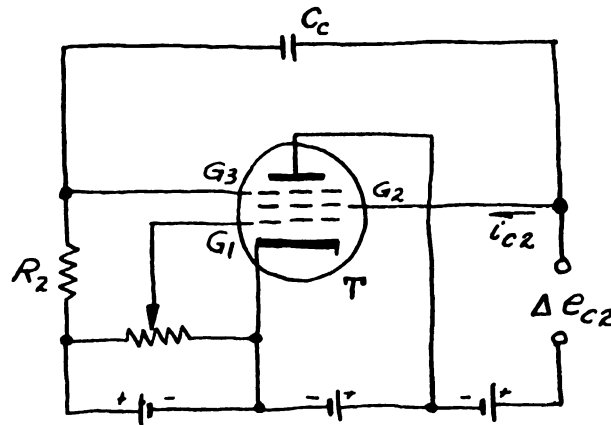


Fig. 2.4 The negative resistance transitron circuit.

Thus it follows that the transitron type oscillator is more stable with time and will have a lower negative resistance. Because the control grid, G_1 , is at a direct current potential the synchronizing voltage may be applied through this electrode.

C H A P T E R I I I

THE MULTIVIBRATOR

3.1 Qualitative Discussion

The zero bias multivibrator is well known and much has been written about its operation. However, the extremely useful characteristics of multivibrators operating with positive grid return are not as well known. The operation of a multivibrator using a positive grid return will be described and compared to that of a conventional multivibrator.

The multivibrator shown in Figure 3.1 consists of a two stage resistance-capacitance coupled amplifier with the output returned to the input so that the circuit is regenerative and satisfies the Barkhausen criterion for sustained oscillations.

The method of oscillation of both types of multivibrators is essentially the same. This method of oscillation follows. If the plate current of tube T_2 is momentarily increased while that of tube T_1 remains constant or decreases, it would start the following chain of reactions:

- (a) The plate voltage of T_2 would decrease;
- (b) the grid of T_1 would become more negative;
- (c) the plate current of T_1 would decrease, al-

lowing its plate voltage increase;

(d) the grid of T_2 would increase, adding to the original change that started the reaction. Because the Barkhausen relationship for oscillators is satisfied, the reaction will progress at a rapid rate until tube T_1 is cutoff, placing its plate voltage at substantially that of the supply, while T_2 has its grid positive with respect to its cathode and considerable drop across its plate load.

The voltage on the grid of T_1 now rises as the coupling capacitor charges, approaching the voltage of the supply grid E_c asymptotically. When the grid of T_1 nears the cutoff voltage, T_1 starts to conduct, so that its plate becomes increasingly negative. This reduces the voltage on the grid of T_2 , causing its plate to become increasingly positive and thus accelerating the already rising voltage on the grid of T_1 . When T_1 becomes sufficiently conducting to make the combined gain of T_1 and T_2 greater than unity, the circuit "flips over"; i.e., the two tubes change places, the grid of T_1 becoming positive with respect to its cathode while the grid of T_2 is driven below the cutoff voltage. The operation is then repeated, the grid of T_2 rising exponentially until T_2 becomes conducting, when a second flip-over occurs, etc.

In the above analysis the effects of the grid current on the multivibrator's operation have been neglected. These effects to a large extent defy exact analytical and quantitative expression. A qualitative discussion follows.⁽⁵⁾ At the reversal points, the grid becomes positive with respect to the cathode thus momentarily limiting the plate voltage to a value less than the plate supply voltage. As the coupling capacitor charges, the grid voltage of the conducting tube decreases allowing its plate voltage to increase; this change in plate voltage is carried over to the grid of the nonconducting tube, modifying the rate of rise of its grid voltage. Thus it is important that the grid-circuit time constant be large compared to the plate-circuit time constant so that the grid current will decrease to a low value at the reversal points and therefore not affect the stability of the multivibrator. Another factor affecting multivibrator stability is the input capacitance of the tubes

(5) Kiebert, Martin V., Jr., and Andrew F. Inglis, Multivibrator Circuits, I.R.E., Vol. 33, No. 8, p. 534, Aug.

which capacitance reduces the signal applied to the grids.

The period of the multivibrator is dependent upon the amplitude of the oscillations, the resistance capacitance combination in both the grid and plate circuits, the synchronizing coupling circuit and voltage, and the voltage to which the grids are returned.

In the positive grid bias multivibrator the period is increased by:

- (a) Increasing the amplitude of oscillations (by increasing the plate load resistance or decreasing the cathode resistance);
- (b) increasing either the resistance or capacitance in the timing circuit, thus decreasing the charging rate of the capacitor; and
- (c) decreasing the grid-return voltage, thus decreasing the rate at which the capacitor charges.

In the zero grid bias multivibrator all save the last statement above hold. Statement "c" does not since the grid bias voltage is an invariant.

It is immediately obvious that of the two aforementioned circuits the positive grid bias one is more inherently stable due to the increased slope of the grid voltage within the operating range. Thus, any incremental change occurring in any of the several

component values or operating conditions will not cause so great a change in the repetition frequency of the positive grid bias multivibrator as in the zero grid bias circuit.

This in itself seems sufficient justification for its inclusion as a crystal controlled generator of standard frequencies.

3.2 Analytical Discussion

The frequency of a multivibrator can be approximated in terms of the constants of Figures 3.1 and 3.2. When a grid is rising exponentially from its maximum negative value (taken at time $t=0$), its instantaneous voltage can be expressed as

$$e_g \cong \left[E_c - (E_c - E_{g_1}) e^{-t/R_g C_e} \right]$$

where $C_e = C + C_{in}$ is the effective capacitance in the discharge circuit. The circuit will reverse when e_g reaches the cutoff value $E_{g_2} = -(E_b/\mu)$; the value of t for this cutoff condition is the half-period of the multivibrator, and thus determines the frequency. The voltage E_{g_1} is found as follows:

$$E_{g_1} = E_{g_3} - (E_b - E_{p_3}) \left(\frac{C}{C + C_{in}'} \right)$$

where

$$E_{g_3} = \frac{R_k E_b}{R_p + R_L + R_k}$$

and

$$E_b - E_{p_3} = \frac{R_L E_b}{R_p + R_L + R_k}$$

The frequency of the multivibrator can now be written

$$f = \frac{1}{2 R_g C_e \ln \frac{\mu (\beta - \gamma)}{\mu \beta + 1}}$$

where

$$\beta = \frac{E_c}{E_b} \quad \text{and} \quad \gamma = \frac{E_{g1}}{E_b}$$

In deriving the frequency equation, the following simplifying approximations have been made. It is assumed that, before a change ever occurs, an equilibrium condition is reached in which the grid of the conducting tube is at the same voltage as its cathode; the plate current is thus determined by the intersection of the load line for the combined plate and cathode loads with the zero-bias plate current. The effective amplification factor is determined by the grid voltage at the effective cutoff point--the point where the over-all gain is just unity. Actually, a very good approximation is obtained if the values for μ and R_p given in the tube manuals are used. It is also assumed that all the grid voltage drop is across the resistance R_g in the grid circuit.

3.3 Multivibrator waveforms

The wave forms of the multivibrator are greatly affected by grid conduction, since this puts a heavy load on the plate circuit of the tube which drives the grid. When the grid is positive, there is a reasonably linear relationship between the grid voltage and the grid current, the ratio for most

small receiver tubes ranging from a maximum of 2000 ohms to a minimum of 500 ohms. In an equivalent circuit diagram, therefore, the grid can be represented by a resistor and a switch in series, the switch being open when the grid is negative and closed when the grid is positive. Because of its small size the equivalent grid-wire resistance need not be known exactly as long as it is of the correct order of magnitude. Many authors have neglected it completely in their mathematical analysis of the multivibrator circuit.

In case the time constant of the circuit involving the non-conducting plate is comparable to that involving the non-conducting grid, the wave forms may differ greatly from the ideal square wave output. This is because the non-conducting plate will not have time to relax to E_b , and the conducting grid will not have time to relax to zero. An exact calculation of the wave form in this case is impossible. The reasons for this are that the cutoff voltage on the non-conducting tube is constantly changing, due to the changing plate voltage, and the grid voltage of the non-conducting tube does not follow an exponential curve.

3.4 Synchronization

When a voltage is injected into the multivibrator this voltage tends to cause the multivibrator

to lock itself to a frequency which bears integral relationship to that of the injected voltage. This ratio is entirely dependent upon the injected voltage's magnitude. Exact details of the control depend upon the way in which the synchronizing voltage is injected and the degree of symmetry between the circuit constants of the two multivibrator tubes.

Increasing the amplitude of the synchronizing frequency causes the multivibrator frequency to be "drawn" in discontinuous steps toward the synchronizing frequency, with the ratio being expressible always as an integer of progressively smaller magnitude. See Figure 3.3. This action is caused by the fact that increasing the amplitude of the injected voltage enables it to neutralize larger condenser charges, and hence to cause a reversal of grid potential before the full charge has had time to leak away.

When the multivibrator is to be controlled, as it is in the present case, the uncontrolled frequency of the oscillator should be slightly less than the value when controlled, and in order to obtain the maximum stability of the control the injected frequency must have the proper amplitude, and the circuit should favor 10:1 division.

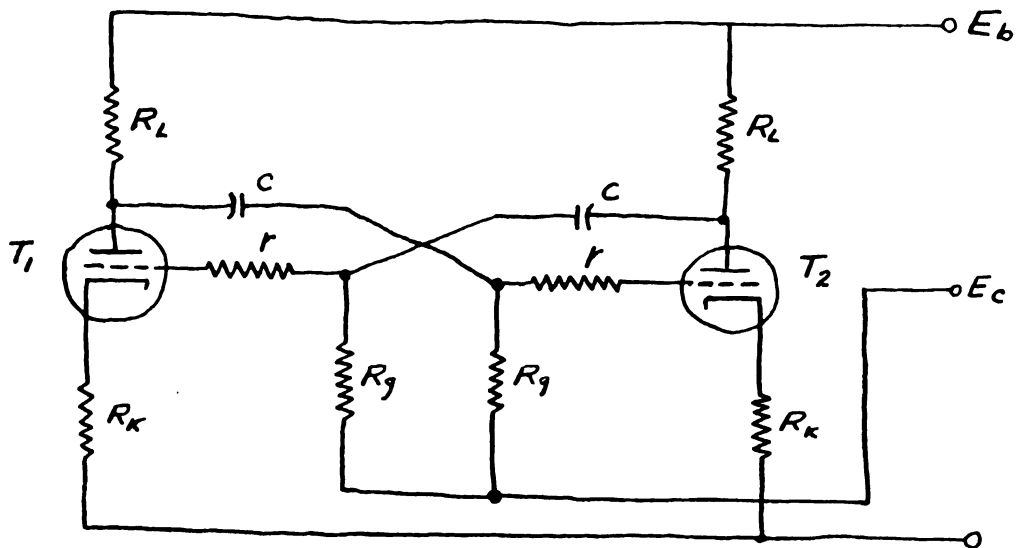


Fig. 3.1 The positive-grid multivibrator

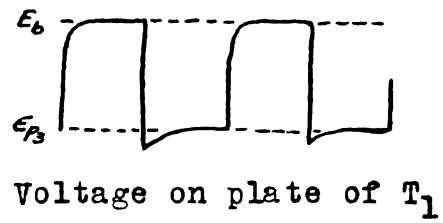
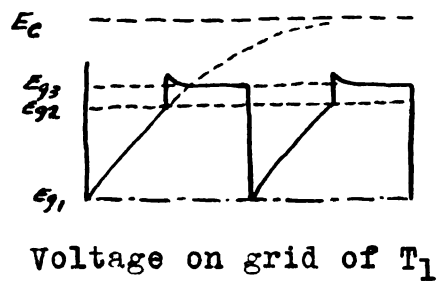


Fig. 3.2 Multivibrator wave shapes

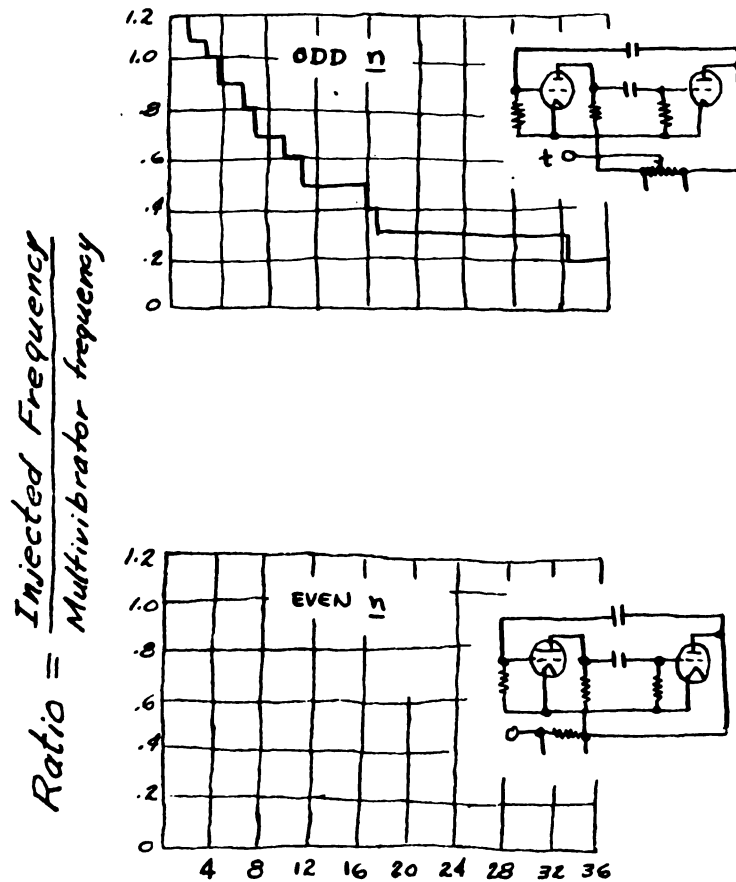


Fig. 3.3

Experimental results showing the effect of increasing the amplitude of the synchronizing voltage, and how certain methods of injecting the voltage tend to favor either even or odd frequency ratios. These results were obtained for a zero bias multivibrator.

C H A P T E R I V

CIRCUIT DESIGN

Considerable work was done in a two month period on the multivibrator described in the previous chapter. Several circuits were set up and qualitative comparison tests were made between the zero bias and positive bias multivibrators with particular attention being paid to their relative stabilities and synchronizing capabilities.

It was found that the stability of the positive bias multivibrator was totally undesirable at the required output level, a level which should provide a usable 10-ke 1000th harmonic. The "breadboard" setup used to test the circuit, although it consisted of the components arranged upon a metal chassis, was extremely susceptible to variations in hand capacitance. The action of the circuit at these times being completely unpredictable, i.e., the fundamental frequency of the circuit suffered extreme variations from the norm, although a synchronizing voltage was applied at the time and adjusted to an optimum value.

The output of the multivibrator was coupled to an oscilloscope in an attempt to determine the wave shape and harmonic content of the output of the multi-

vibrator. Various methods of coupling were devised which consisted essentially of condenser isolation but nevertheless the oscilloscope at all times loaded the circuit and at times the multivibrator was completely thrown out of oscillation. When the circuit did oscillate it was overloaded so much when coupled to the oscilloscope that the voltage output curve was characterized by its extreme flatness of slope. This type of output is completely useless as it has negligible high harmonic content.

A surplus BC 221 Frequency Meter was used throughout in attempting to determine the operating frequency by the harmonic location method. Due to the obvious limitations of the instrument, i.e., its several coincident and simultaneous operating ranges, completely contradictory and misleading results were obtained and it never was determined at what frequency the fundamental oscillation occurred.

Associated circuits could have been devised that would provide the required output and stability using pentode type multivibrators, clippers, etc., but since this would yield results which could be obtained only with more intricate, elaborate circuits and also could not be incorporated into the chassis available. Therefore the multivibrator was discarded

in toto in favor of a transitron type, sub-harmonic, synchronized generator which would yield the same results with less trouble.

The transitron oscillator, because the oscillation occurs between the second and third grids, can have its synchronizing voltage applied to the first or control grid without additional loading or its accompanying unpleasant results. Secondly, since the circuit containing the negative resistance has across it the inductive-capacitative combination and not the RC combination the synchronizing voltage may have a constant amplitude at all operating frequencies and is not dependent upon the slope of the grid voltage curve. This was considered an additional advantage over the multivibrator. Lastly, the LC oscillator circuit has in itself an inherent stability and selectivity response which the RC type circuit lacks. This was considered an aid in alleviating the effects of field variations which so noticeably altered the expected response of the multivibrator.

After the transitron circuit was set up the results improved considerably. The output was recorded to frequencies as high as 10 megacycles with the 100 and 50 kc harmonic circuits in operation on a super-heterodyne receiver.

The circuit control by the synchronizing voltage is not too critical and it was determined that the optimum synchronizing voltage for the 20kc and 10kc oscillators were values which did not differ by two great an amount and so a compromise was established that enabled the transitron to oscillate at all three sub-harmonics.

The sub-harmonic generator was tested and found to be capable of oscillation at the fundamental of 100kc and the sub-harmonic fundamentals of 50kc, 20kc, and 10kc. Due to the fact that the 5mc, fixed tuned, WWV receiver had not been completed at the time considerable difficulty was experienced in the final adjustment of the oscillators using this receiver but was done on the superheterodyne.

Tuning the frequency meter caused a multitude of null points to occur and since the lowest frequency capable of being read on this meter is 125kc additional error was thus introduced. Also it seemed very unlikely that this instrument should have an exactly linear calibration curve.

Noise was very prevalent and increased in amplitude as the frequency increased until it completely suppressed the output signal.

It was surmised that this occurred because of beat notes between the 10kc harmonics and the synchroniz-

ing signal. These would occur if the 10kc oscillator were not adjusted exactly to 10kc.

A variable frequency generator was obtained which was capable of giving an output up to 10mc. At this time the WWV receiver was available and therefore the 50th harmonic of the 100kc oscillator was zero beat against the 5mc fundamental standard of frequency with the aid of the variable frequency generator. Error was likely to have been introduced at this step since this receiver had not had incorporated within it any means of eliminating the audio modulation present on the carrier signal. Also it did not have any meter with which zero beat with the 5mc carrier could be exactly determined.

Stability tests were run on the 100kc oscillator by comparing its 50th harmonic with the 5mc standard with the results tabulated. (See Fig. 4.1).

It is seen from the schematic circuit diagram that the frequency determining elements are connected through a rotary switch to the second grid of the vacuum tube V2 and that these control the fundamental frequency of the transitron circuit. Thus the transitron oscillator is only operative when other than the 100kc harmonic points are desired. Because of this the stability of the transitron oscillator should be identical with that of the 100kc oscillator.

Effective, or R.M.S., voltage measurements were made using a vacuum tube voltmeter which had various values of capacitance inserted in its input lead in an attempt to determine the energy content of various portions of the harmonic output spectrum. (See graph, Fig. 4.2).

From this data it was concluded that the energy was fairly well distributed throughout the spectrum with a fairly constant rate of decrease, with increasing frequencies, of energy content in the low and medium range of harmonics. The abrupt decrease in the high portion of the spectrum was attributed to the effects of stray capacitance and of field variations for these frequencies.

Vacuum tube V1, a 6Y6, is the oscillator tube. The circuit incorporating this tube is essentially a tuned-grid-tuned-plate oscillator circuit. The grid circuit has as its frequency determining element a crystal ground to oscillate at approximately 100kc. The output of the oscillator is taken from the inductive capacitive combination across the anode and ground. The capacitor is variable and provides the fine adjustment (of about ± 40 cycles) necessary to set the oscillator at exactly 100 kc.

Vacuum tube V2, a 6SN7, is the buffer amplifier tube. The circuit incorporating this is the

standard form of a resistance capacitance coupled amplifier. It serves to stabilize the output of the oscillator circuit against variations in loading and circuit parameter variations.

Vacuum tube V3, a 6SJ7, is the transitron oscillator tube. The circuit incorporating this tube is the transitron oscillator section. This oscillator is capable of oscillating at each of the three required sub-harmonics of 100kc. Switch "1" determines which combination of inductance and capacitance will be present in the circuit and thus determines the frequency of oscillation. It is seen that a synchronizing voltage which synchronizes the oscillations of this tube to the proper harmonic relationship with the 100kc oscillator will be present on the control grid of V3.

Vacuum tube V4, a 6AC7, is an amplifier tube. It serves to amplify its input to the required output level necessary to drive tube V5. The resistive-capacitative input network serves as a voltage divider which, at each of its four possible values, serves to provide an input of the proper level.

Vacuum tube V5, an 802, is the harmonic power amplifier tube. The circuit incorporating the tube is one of the many possible circuits which provides graded amplification for the harmonically rich output. This circuit attenuates the lower frequency components and

peaks the higher frequency components thus providing a reasonably constant amplitude for the harmonics of the output voltage. The switch in the output circuit ending in the jacks is in series with a capacitutive-inductive voltage dividing network to provide a fairly constant output impedance. This is a high impedance output and care should be taken in coupling to it as improper matching may completely eliminate the higher harmonics of the two lowest sub-harmonic fundamentals by causing an r.f. short circuit.

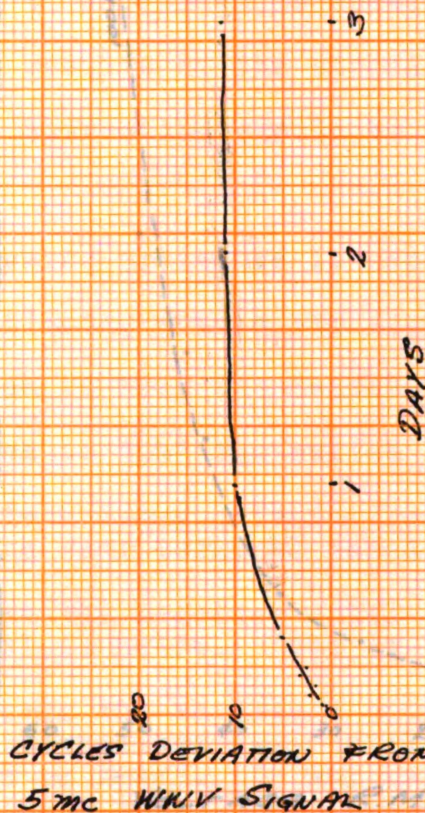
Vacuum tube V6, a 6SJ7, is the transitron modulator oscillator tube. The circuit consists of the standard transitron oscillator network whose output is used to modulate the harmonic power amplifier, V5, with a 350cps audio signal so as to make the harmonics identifiable.

Vacuum tube V7, a 6AC7, is the sinusoidal amplifier tube. This tube and its associated circuit provide amplification for the lowest frequencies and is not designed to intentionally introduce harmonic distortion of appreciable amplitude. The circuit is a standard resistance capacitance network and its output is stable and may be used as a standard source of the same stability as the master oscillator.

STABILITY TESTS

A 72 HOUR STABILITY TEST USING THE TEST OSCILLATOR EE 4321. THE CORRECT ALIGNMENT WAS INDICATED BY ZERO BEAT METER ON THE OSCILLATOR.

NOTE: IN THE FIRST ONE HOUR PERIOD THERE WERE ERRATIC VARIATIONS WHICH COULD NOT BE MEASURED EXACTLY.



HARMONIC VOLTAGES SPECTRUM DISTRIBUTION

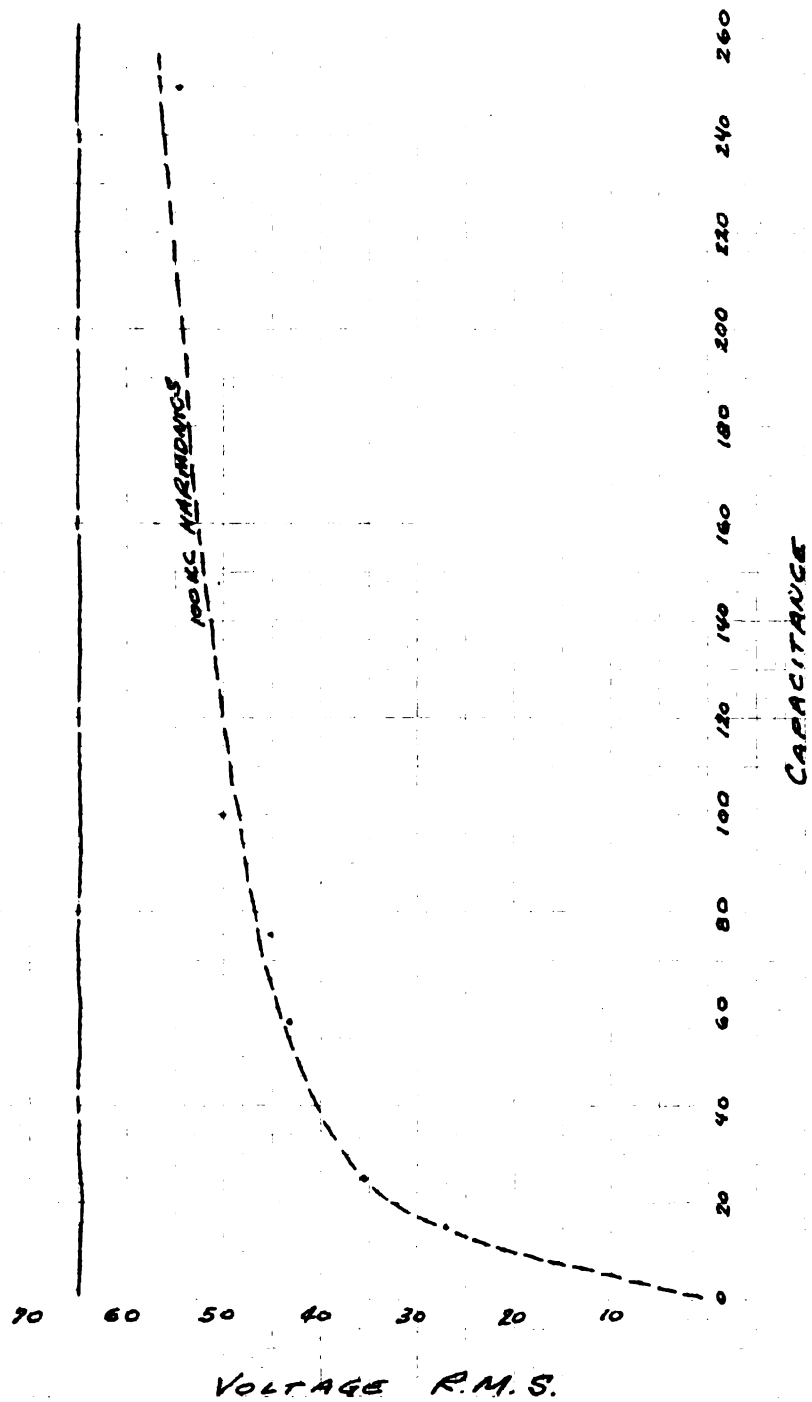


Fig 4.2

CHAPTER V

CONCLUSIONS AND OPERATING INSTRUCTIONS

This frequency generator will provide very strong 100kc points up to and above 10mc at which frequency a WWV standard frequency modulated carrier is located. This signal and not the 5mc WWV signal may occasionally have to be used in making any adjustments that may be necessary in correcting the fundamental frequency of the 100kc oscillator as the 5mc WWV signal has been found to suffer quite severely from fading. Fig. 4.1 shows the results of the stability test and it is evident that correction should be only occasionally necessary.

The following procedure is necessary to zero beat the 100kc oscillator with a WWV signal:

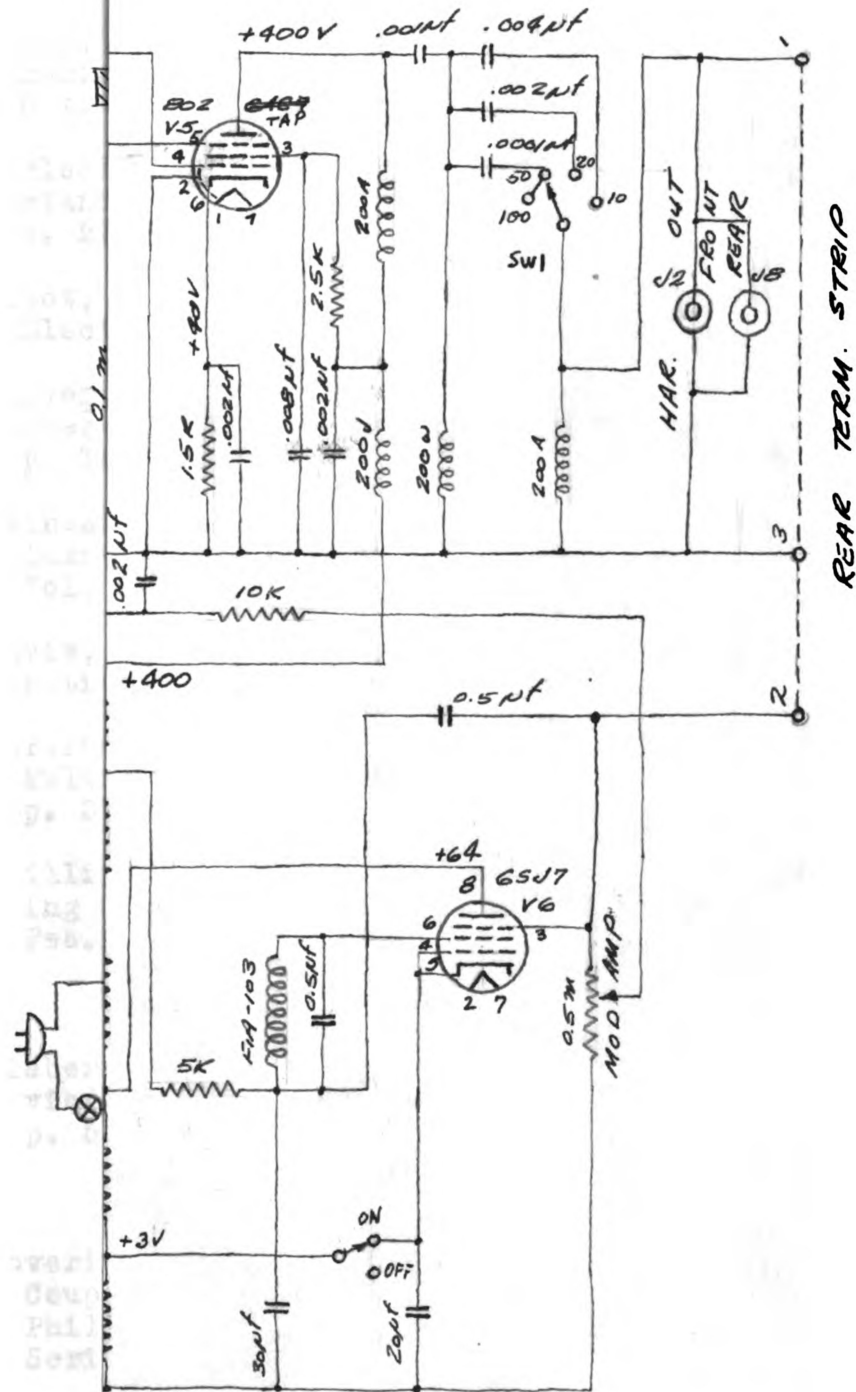
1. Switch to "On" the switch labeled "Power".
2. Switch to "On" the switch labeled "Plate".
3. Couple a dummy antenna from terminal "1" of the rear terminal panel to a receiver.
4. Adjust the receiver until the desired WWV signal is heard. (5mc or 10mc).
5. Increase the amplitude of modulation and adjust receiver dial until a 100kc harmonic is heard. It may be identified by its 330 c.p.s. tone.
6. Adjust the "100kc adjustment" screw until the proper harmonic is superimposed on the

WV carrier. This may be done during the quiet periods, when there is no audio modulation present on the WV carrier, by turning the switch labeled "Modulation" to the "Off" position and zero beating the two unmodulated carriers.

7. The 50kc, 20kc, and 10kc corrections may be made in a similar manner.
8. To avoid frequent adjustment the switch labeled "Power" should be left in the "On" position.

The various methods of specifically measuring an unknown signal will be found in the Manual of Operating Instructions.

This standard should not be used for at least one hour after the power has been turned on as this is the period of greatest instability. After this time the standard has sufficient stability for most applications.



BIBLIOGRAPHY

1948

- Clapp, J. K., Frequency Measurement by Sliding Harmonics, Proc. I. R. E., Vol. 36, No. 10, p. 1285, Oct.
- Terlecki, R., and J. W. Whitehead, Two Portable Sub-standards of Frequency, Jour. Sci. Instr., Vol. 25, p. 237, July
- Abbot, A. E., Multivibrator Design by Graphic Methods, Electronics, Vol. 21, p. 118, June
- Silver, M., and A. Shadowitz, High-Ratio Multivibrator Frequency Divider, Elec. Commun. (London), Vol. 25, p. 160, June
- Feinberg, R., On the Performance of the Push-Pull Relaxation Oscillator (Multivibrator), Phil. Mag., Vol. 39, p. 268, Apr.
- Davis, K. H., Multivibrator Step-Down by Fractional Ratios, Bell Lab. Rec., Vol. 26, p. 114, March
- Bertram, Sidney, The Degenerative Positive-Bias Multivibrator, Proc. I. R. E., Vol. 36, No. 2, p. 277, Feb.
- Phillips, F. C. F., A Direct Reading Frequency Measuring Set, Jour. I.R.E. (Brit.), Vol. 8, p. 4, Jan. & Feb.

1945

- Kiebert, Martin V., Jr., and Andrew F. Inglis, Multivibrator Circuits, Proc. I.R.E., Vol. 33, No. 8, p. 534, Aug.

1944

- Lovering, W. F., A Push Pull Resistance-Capacity Coupled Oscillator, London, Edinburgh and Dublin Philosophical Magazine and Journal of Science, 7th Series, Vol. 35, No. 250, p. 715, Nov.
- Greenidge, R. M. C., The Mounting and Fabrication of Plated Quartz Crystal Units, Bell Sys. Tech. Jour., Vol. 23, p. 234

Sykes, R. A., Principles of Mounting Quartz Plates,
B.S.T.J., Vol. 23, p. 178

Sykes, R. A., Modes of Motion in Quartz Crystals, the
Effects of Coupling and Methods of Design, B.S.T.J.,
Vol. 23, p. 52

Mason, W. P., and R. A. Sykes, Low-Frequency Quartz
Crystal Cuts Having Low Temperature Coefficients,
Proc. I.R.E., Vol. 32, p. 208

Bokovoy, J. A., Quartz Crystals-Development & Appli-
cation, Elec. Comm., Vol. 21, p. 233

1943

Druesne, M. A. A., Quartz Crystals, Communications,
Vol. 23, p. 46f, Sept.

Mason, W. P., Quartz Crystal Applications, B.S.T.J.,
Vol. 22, p. 178

1942

Bedford, A. V., and G. L. Fredendall, Analysis, Syn-
thesis and Evaluation of the Transient Response of
Television Apparatus, Proc. I.R.E., p. 440, Oct.

1941

Booth, C. F., The Application and Use of Quartz Cry-
stals in Telecommunications, Jour. I.E.E., Vol. 88,
Part III, p. 97, June

Bartelink, E. H. B., A Wide-band Square-wave Generator,
Trans. A.I.E.E., Vol. 60, p. 371

1940

Mason, W. P., A New Quartz Crystal Plate, Designated
the GT, Which Produces a Very Constant Frequency over
a Wide Temperature Range, Proc. I.R.E., Vol. 28,
p. 220, May

Roberts, Walter Van B., The Limits of Inherent Fre-
quency Stability, R.C.A. Rev., Vol. 4, p. 478, April

Mason, W. P., Low Temperature Coefficient Quartz Cry-
stals, B.S.T.J., Vol. 19, p. 74, Jan.

Baldwin, C. F., Quartz Crystals, G. E. Review, Vol. 43, p. 188

Chakravarti, S. P., On the Nature of Negative Resistance and Negative Resistance Sections, Phil. Mag., Vol. 30, p. 294

1939

Herr, Donald L., Oscillations in Certain Non-Linear Driven Systems, Proc. I.R.E., Vol. 27, p. 396, June

Lampkin, G. F., An Improvement in Constant Frequency Oscillators, Proc. I.R.E., Vol. 27, p. 199, March

Brunetti, Clelio, The Transitron Oscillator, Proc. I.R.E., Vol. 27, No. 1, p. 88

1938

Meachem, L. A., The Bridge Stabilized Oscillator, Proc. I.R.E., Vol. 26, p. 1278, Oct.

Anderson, J. E., Frequency Characteristics of Piezo-electric Oscillators, Electronics, p. 22, Aug.

Stevenson, G. H., Stabilized Feedback Oscillators, B.S.T.J., Vol. 17, p. 458, July

1937

Seeley, S. W., and C. N. Kimball, Analysis and Design of Video Amplifiers, R.C.A. Review, p. 171, Oct.

Sabaroff, S. A., A Voltage Stabilized High Frequency Crystal Oscillator Circuit, Proc. I.R.E., Vol. 25, p. 623

Hight, S. C., and G. W. Willard, A Simplified Circuit for Frequency Substandards Employing a New Type of Low-frequency Zero-temperature Coefficient Quartz Crystal, Proc. I.R.E., Vol. 25, p. 549, May

Lamb, J. J., A Practical Survey of Pentode and Beam Tube Crystal Oscillators for Fundamental and Second Harmonic Output, QST, Vol. 21, p. 31, Apr.

Harnwell, G. P., & J. B. H. Kuper, Laboratory Frequency Standard, The Review of Scientific Instruments, Vol. 8, March, p. 83

Hight, S. C., Quartz Plates for Frequency Sub-
Standards, Bell Labs. Rec., Vol. 16, p. 21

1936

Diehl, W. F., A New Piezo-electric Quartz Crystal Hold-
er with Thermal Compensation, R.C.A. Rev., Vol. 1,
p. 86, Oct.

VanDyke, Karl S., A Determination of Some of the Prop-
erties of the Piezoelectric Quartz Resonator, Proc.
I.R.E., Vol. 23, p. 386, Apr.

Koga, Isaac, Notes on Piezoelectric Quartz Crystals,
Proc. I.R.E., Vol. 24, p. 510, March

leCorbeiller, Ph., The Non-linear Theory of the Main-
tenance of Oscillations, Jour. I.E.E., Vol. 79,
p. 361

1935

Gager, F. M., and J. B. Russell, Jr., A Quantitative
Study of the Dynatron, Proc. I.R.E., Vol. 23, No.
12, p. 1536, Dec.

Mason, W. P., An Electromechanical Representation of
a Piezo-electric Crystal Used as a Transducer, Proc.
I.R.E., Vol. 23, p. 1252, Oct.

Herold, E. W., Negative Resistance and Devices for
Obtaining It, Proc. I.R.E., Vol. 23, p. 1201, Oct.

Gager, F. Malcolm, The Grid-Coupled Dynatron, Proc.
I.R.E., Vol. 23, No. 9, p. 1048, Sept.

Baldwin, C. F., and S. A. Bokovoy, Practical Operating
Advantages of Low Temperature Frequency Coefficient
Crystals, QST, Vol. 19, p. 26, Jan.

Bechmann, R., Researches on Natural Elastic Vibrations
of Piezo-Electrically Excited Quartz Plates, Zeit.
f. Technisch Physick, Vol. 16, No. 12, p. 525

1934

Lack, F. R., G. W. Willard, and I. E. Fair, Some Im-
provements in Quartz Crystals Circuit Elements,
B.S.T.J., Vol. 13, p. 453, July

Mason, W. P., Electrical Wave Filters Employing Quartz
Crystals as Elements, B.S.T.J., Vol. 13, p. 405,
July

Hayasi, Tatu, The Inner-Grid Dynatron and Duodynatron, Proc. I.R.E., Vol. 22, No. 6, p. 751, June

Meahl, M. R., Quartz Crystal Controlled Oscillator Circuits, Proc. I.R.E., Vol. 22, p. 732

1933

Williams, N. H., Modes of Vibration of Piezoelectric Crystal, Proc. I.R.E., Vol. 21, p. 990, July

Groszkowski, J., The Interdependence of Frequency Variation and Harmonic Content and the Problem of Constant Frequency Oscillators, Proc. I.R.E., Vol. 21, No. 7, p. 958, July

Lamb, J. J., A More Stable Crystal Oscillator of High Harmonic Output, QST, Vol. 17, p. 30, June

Scroggie, M. G., Applications of the Dynatron, Wireless Eng. and Eng. Wireless, Vol. 10, p. 529

Colebrook, F. M., Voltage amplification with high selectivity by means of the dynatron circuit, Wireless Eng. and Eng. Wireless, Vol. 10, p. 69

1932

Mackinnon, K. A., Crystal Control Applied to the Dynatron Oscillator, Proc. I.R.E., Vol. 20, p. 1689

Peterson, H. O., and A. M. Braaton, The Precision Frequency Measuring System of R.C.A. Communications, Inc., Proc. I.R.E., Vol. 20, No. 6, p. 941, June

Colwell, R. C., The Vibrations of Quartz Plates, Proc. I.R.E., Vol. 20, No. 5, p. 808, May

Hougaard, O. M., Application of Quartz Plates to Radio Transmitters, Proc. I.R.E., Vol. 20, p. 767, May

Kusunese, Y., and S. Ishikawa, Frequency Stabilization of Radio Transmitters, Proc. I.R.E., Vol. 20, p. 310, Feb.

Heaton, Vincent E., and E. G. Lapham, Quartz Plate Mountings and Temperature Control for Piezo Oscillators, Proc. I.R.E., Vol. 20, p. 261, Feb.

1931

Llewellyn, F. B., Constant Frequency Oscillators, Proc. I.R.E., Vol. 19, p. 2063, Dec.

- Dingley, Edward N., Jr., Development of a Circuit for Measuring the Negative Resistance of Pliodynatron, Proc. I.R.E., Vol. 19, No. 11, p. 1948, Nov.
- Andrew, Victor J., The Adjustment of the Multivibrator for Frequency Division, Proc. I.R.E., Vol. 19, No. 11, p. 1911, Nov.
- Boella, M., Performance of Piezo Oscillators and the Influence of Decrement of Quartz on the Frequency of Oscillation, Proc. I.R.E., Vol. 19, No. 7, p. 1252, July
- Koga, I., Note on the Piezoelectric Quartz Oscillating Crystal Regarded from the Principle of Similitude, Proc. I.R.E., Vol. 19, p. 1022
- Wheeler, L. P., An Analysis of a Piezoelectric Oscillator Circuit, Proc. I.R.E., Vol. 19, p. 627
- Mogel, Hans, Some Methods of Measuring the Frequency of Short Waves, Proc. I.R.E., Vol. 19, No. 2, p. 195, Feb.
- Colebrook, F. M., The dynatron oscillator, Wireless Eng. and Eng. Wireless, Vol. 8, p. 581

1930

- Clapp, James K., Temperature Control for Frequency Standards, Proc. I.R.E., Vol. 18, p. 2003, Dec.
- Koga, I., Characteristics of Piezoelectric Quartz Oscillators, Proc. I.R.E., Vol. 18, p. 1935
- Clapp, J. K., Interpolation Methods for Use with Harmonic Frequency Standards, Proc. I.R.E., Vol. 18, p. 1575, Sept.
- Heaton, V. E., and W. H. Brattain, Design of a Portable Temperature Controlled Piezo Oscillator, Proc. I.R.E., Vol. 18, No. 7, July
- Watanabe, Yasusi, Some Remarks on the Multivibrator, Proc. I.R.E., Vol. 18, No. 2, Feb.
- Harrison, J. R., Push-Pull Piezoelectric Oscillator Circuits, Proc. I.R.E., Vol. 18, p. 95

1929

Jimbo, Seikichi, Measurement of Frequency, Proc. I.R.E., Vol. 27, No. 11, p. 2011, Nov.

Lack, F. R., Observations on Modes of Vibration and Temperature Coefficient of Quartz Crystal Plates, Proc. I.R.E., Vol. 17, p. 1123, July

Marrison, W. A., A High Precision Standard of Frequency, Proc. I.R.E., Vol. 17, p. 1103, July

Hall, E. L., A System for Frequency Measurements Based on a Single Frequency, Proc. I.R.E., Vol. 17, No. 2, p. 272, Feb.

Hull, L.M., and J. K. Clapp, A Convenient Method for Referring Secondary Frequency Standards to a Standard Time Interval, Proc. I.R.E., Vol. 17, p. 252, Feb.

1928

Hund, August, Notes on Quartz Plates, Air Gaps Effect, and Radio-frequency Generation, Proc. I.R.E., Vol. 16, p. 1072, Aug.

Wheeler, L. P., and W. E. Bower, A New Type of Standard Frequency Piezoelectric Oscillator, Proc. I.R.E., Vol. 16, p. 1035

Marrison, W. A., Thermostat Design for Frequency Standard, Proc. I.R.E., Vol. 16, p. 976, July

Worrall, Robert H., and Raymond B. Owens, The Navy's Primary Frequency Standards, Proc. I.R.E., Vol. 16, No. 6, p. 778, June

VanDyke, K. S., The Piezo-electric Resonator and Its Equivalent Network, Proc. I.R.E., Vol. 16, p. 742, June

Cady, W. G., Bibliography on Piezoelectricity, Proc. I.R.E., Vol. 16, p. 521, No. 4, April

Crossley, A., Modes of Vibration in Piezo-Electric Crystals, Proc. I.R.E., Vol. 16, No. 4, p. 416, April

Horton, J. W., and W. A. Marrison, Precision Determination of Frequency, Proc. I.R.E., Vol. 16, p. 137

1927

- Harrison, J. R., Piezo-Electric Resonance and Oscillatory Phenomena with Flexural Vibrations in Quartz Plates, Proc. I.R.E., Vol. 15, No. 12, p. 1040, Dec.
- Hitchcock, R. C., Mounting Quartz Oscillator Crystals, Proc. I.R.E., Vol. 15, p. 802, Nov.
- Hund, A., Notes on Piezoelectric Generators with Small Back Action, Proc. I.R.E., Vol. 15, No. 8, Aug.
- Strook, M. S., Standard Frequency Dissemination. Proc. I.R.E., Vol. 15, No. 8, p. 727, Aug.
- Royden, George T., The Frequency Checking Station at Mare Island, Proc. I.R.E., Vol. 15, No. 4, p. 313, Apr.
- Meissner, A., Piezo-Electric Crystals at Radio Frequencies, Proc. I.R.E., Vol. 15, No. 4, p. 281, Apr.

1926

- Dye, D. W., Piezo Electric Quartz Resonator and Its Equivalent Electrical Circuit, Proc. Phys. Sec. (London), Vol. 38, p. 399
- Terry, E. M., The Dependence of the Frequency of Quartz Piezoelectric Oscillators upon Circuit Constants, Proc. I.R.E., Vol. 16, p. 1486
- Hund, A., Uses and Possibilities of Piezoelectric Oscillators, Proc. I.R.E., Vol. 14, No. 4, p. 447, Aug.
- van der Pol, Balth, On Relaxation Oscillations, Phil. Mag., Vol. 2, p. 978, Nov.

1925

- Hund, A., A Method of Measuring Radio Frequency by Means of a Harmonic Generation, Proc. I.R.E., Vol. 13, No. 2, Apr.

1924

- Cady, W. G., An International Comparison of Radio Wavelength Standards by Means of Piezo-Electric Resonators, Proc. I.R.E., Vol. 12, No. 6, p. 805, Dec.

1. The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that proper record-keeping is essential for the transparency and accountability of the organization. This section also outlines the various methods used to collect and analyze data, ensuring that the information is reliable and up-to-date.

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4. The fourth part of the document provides a summary of the key findings and conclusions. It reiterates the importance of the changes and the successful outcome of the implementation. This section also offers recommendations for future actions and areas for further research.

5. The final part of the document is a conclusion that summarizes the entire report. It expresses the confidence in the proposed changes and the commitment to ongoing improvement. This section also includes a statement of appreciation for the support and collaboration of all stakeholders involved in the process.

van der Pol, B., Non Linear Theory of Electric Oscillations, Proc. I.R.E., Vol. 22, p. 1051

1923

Dunmore, Francis W., and Francis H. Engel, a Method of Measuring Very Short Radio Wave Lengths and Their Use in Frequency Standardization, Proc. I.R.E., Vol. 11, No. 5, p. 467, Oct.

Pierce, G. W., Piezo-electric Crystal Resonator and Crystal Oscillators Applied to the Precision Calibration of Wavemeters, Proc. Am. Acad., Vol. 59, p. 81

1922

Cady, W. G., The Piezo-electric Resonator, Proc. I.R.E., Vol. 10, No. 2, p. 83

1919

Abraham, H., and E. Block, Mesure en valeur absolue des périodes oscillations electriques de haute fréquence, Annal d. Phys., Vol. 12, p. 237, Sept.-Oct.

1918

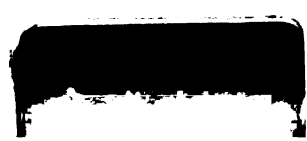
Cordes, H. G., Theory of Free and Sustained Oscillations, Proc. I.R.E., Vol. 6, No. 3, p. 167, June

1916

Kennelly, A. E., The Impedances, Angular Velocities, and Frequencies of Oscillating Current Circuits, Proc. I.R.E., Vol. 4, No. 1, p. 47, Feb.

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