A NEW TYPE
RESISTANCE-CAPACITY OSCILLATOR

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June 9, 1939

TABLE OF CONTENTS

II General Theory

TABLE OF PLATES

I OBJECT

At the present time the field of choice of a variable frequency oscillator for laboratory use is limited to two classes of instruments. The commonest is the conventional coil and condenser type in which the desired frequency is obtained by an inductance-capacity combination as given by a calibration chart. Although an instrument of this type is capable of excellent frequency stability and an almost unlimited range of frequencies, it has several disadvantages. Foremost, is that it is slow and awkward to use if the frequency must be changed often. Owing to the iron cored inductances required for low frequency operation, it must have considerable weight, thus making its portability quite low. An example of an oscillator of this type is the Western Electric 8A oscillator. The second class of oscillator is the beat-frequency type. An oscillator of this type can be made to cover a wide range of frequencies by the use of a single dial, and for this reason is particularly suited for general laboratory use. However, it has the inherent disadvantage of unsatisfactory stability at low frequencies and difficulties of mechanical construction and layout. To overcome these difficulties in the higher quality beat-frequency oscillator, it has been found necessary to increase the weight with the result that the portability has again been reduced. An example of a high quality oscillator of this type is the General Radio No. 713B.

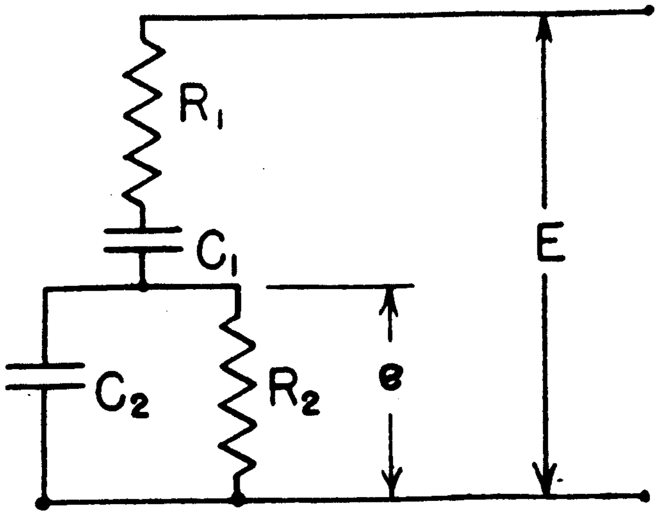
The author has felt that there is a real need of a new type oscillator that would combine the stability of the coil-condenser type, the flexability of operation of the beat-frequency type, and still be light and portable as well as simple in construction and adjustment.

The object of this research has been the development, construction, and testing of such an oscillator.

II GENERAL THEORY

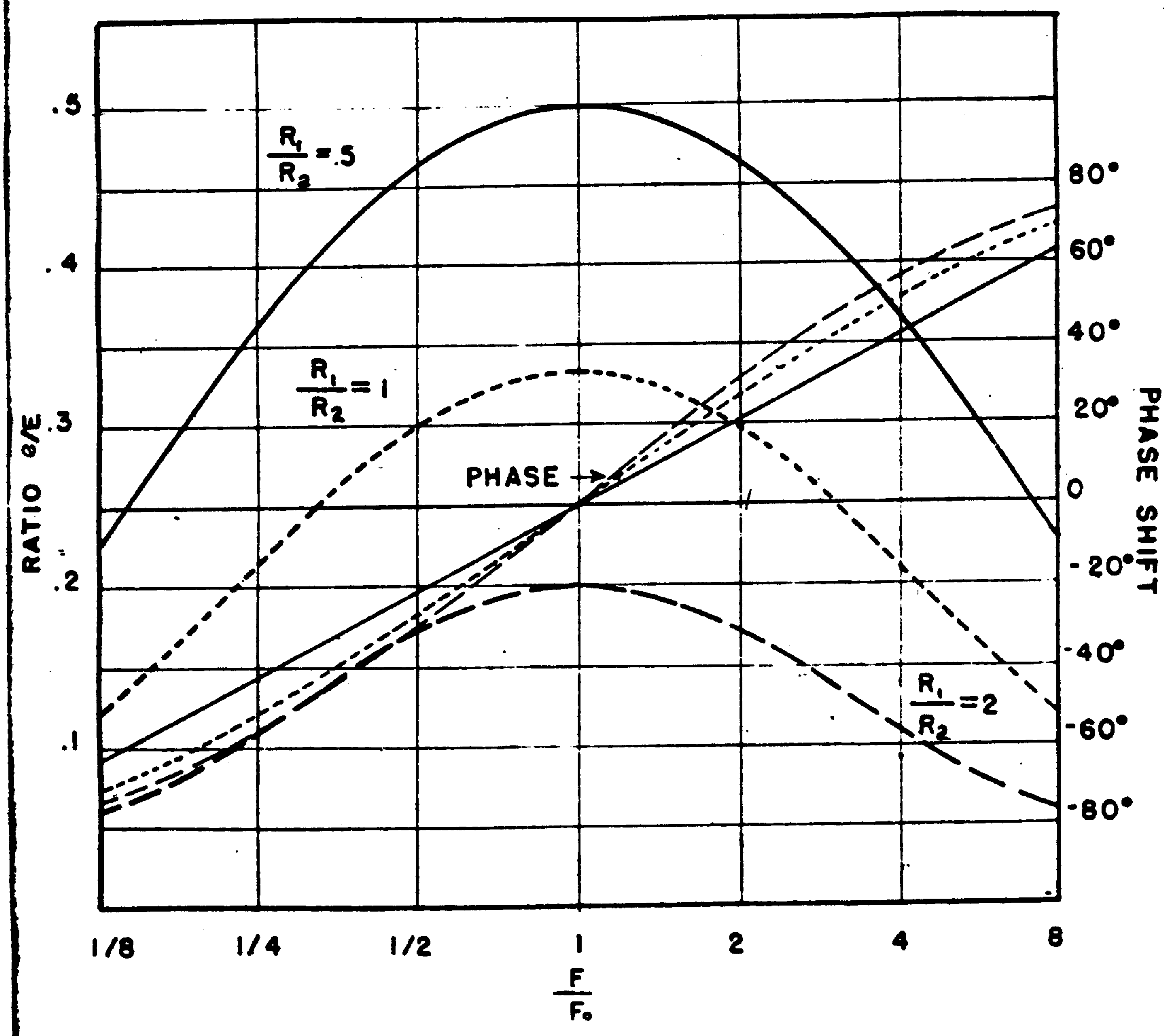
Frequency Determining Network

This is a new type of oscillator in which the frequency determining element is a resistance-capacity network. This network is characterized by having a resonant frequency that is inversely proportional to the product of resistance and capacity. This fact allows a much greater change in resonant frequency for a given change in capacity than in the normal inductance-capacity oscillating circuit, where the resonant frequency is inversely proportional to the square root of capacity. Thus as a variable broadcast condenser is capable of a capacity change of at least ten to one, a condenser of this type with suitable fixed resistances could be made to cover the entire audio frequency range in just three steps: 20 to 200, 200 to 2000, and 2000 to 20,000 cycles. Furthermore, all these ranges could be made to read on a single scale with multiplying factors of 1, 10, and 100. However, the discrimination of a network of this type in favor of the desired frequency is only very slight. As a matter of fact it is almost exactly equivalent to a normal inductance-capacity resonant circuit with a "Q" of about 1/3. In Fig. 1 are shown the resistance capacity network, the definition of the resonant frequency, and curves of frequency discrimination and phase shift in the vicinity of resonance for different



$$\omega_0 = \frac{1}{R_1 C_1} = \frac{1}{R_2 C_2}$$

$$\left(\frac{e}{E}\right)_{MAX.} = \frac{R_2}{2R_1 + R_2}$$



values of the parameters R and C.

When a circuit with a very low "Q" is used as the frequency determining element of an oscillator, there are two factors that may cause unsatisfactory operation. The first and most important of these is that the percentage change in frequency per degree of phase shift is quite high. The second is that discrimination against any harmonics that might be produced in the amplifier is very poor.

Nyquist has shown that for oscillation to start in an amplifier, the net phase shift around the amplifier and feedback network combined must be $2\pi n$ radians, and that the net gain must be exactly one. This means that if there is a phase shift of $\Delta\beta$ in the amplifier circuit, then there must be a phase shift of $-\Delta\beta$ in the feedback or frequency determining network, if oscillations are to continue. On inspection of the curves of Fig. 1, it may be seen that for the case in which $R_1 = R_2$ and $C_1 = C_2$ that a one degree change in phase shift can only be achieved by a 2.8 per cent change in frequency. Thus if in an oscillator of this type the maximum allowable frequency deviation is ± 1 per cent, then the maximum phase shift must be less than 0.3 degrees. This requirement then demands that the amplifier that is associated with this resistance-capacity network be very stable with respect to phase shift.

The suppression of harmonics is also a factor in the stability of an oscillator. If distortion were present in the amplifier, some of the cross products of modulation between the higher order harmonics might be of the fundamental frequency, but in general would not be of the same phase. This would be equivalent to introducing a phase angle in the amplifier that would be dependent on the distortion and hence on the amplitude of oscillation. For this reason there must be some amplitude-limiting device in the amplifier circuit that will not introduce an appreciable amount of distortion.

Design of the Amplifier Circuit

From the above analysis, the requirements of the associated amplifier circuit may be set down:

(1) The total phase shift around the amplifier circuit must be $2\pi n$ radians.

(2) The amplifier must have a gain of just $R_1 + 2R_2/R_1$.

(3) The deviation in phase shift with changes in plate voltage or tube characteristics should be as low as possible.

(4) Some means of amplitude limiting should be used that will not introduce harmonic distortion.

The first of these requirements may be met by the use of a two-stage amplifier. The same result might be achieved by the use of a single stage and a transformer, but in this case it would be difficult to find a transformer which would operate satisfactorily over a wide range of frequencies.

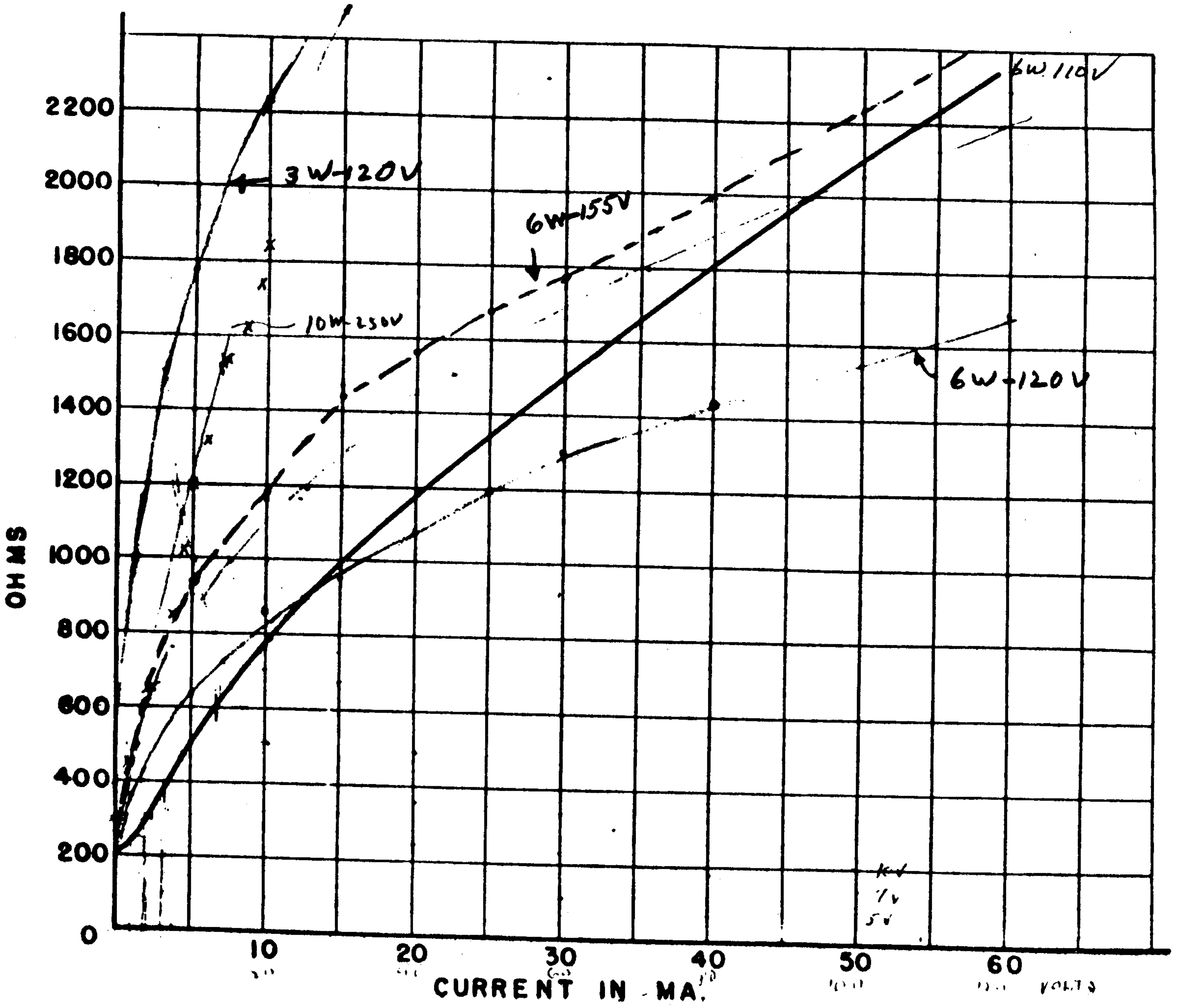
The next three requirements may be met by the use of enough negative feedback to reduce the gain of the amplifier to the required value. When negative feedback is applied to an amplifier, the normal phase shift is reduced by a factor of about $A\beta$, where A is the normal gain of the amplifier without feedback, and β is the fraction of the output voltage that is fed back to the input. Thus if the gain of the amplifier without feedback, A, is about 150, as it might be in practice, and β is 1/3, the phase shift will be reduced by a factor of about 50 to 1. This then makes the phase shift substantially independent of tubes or external conditions.

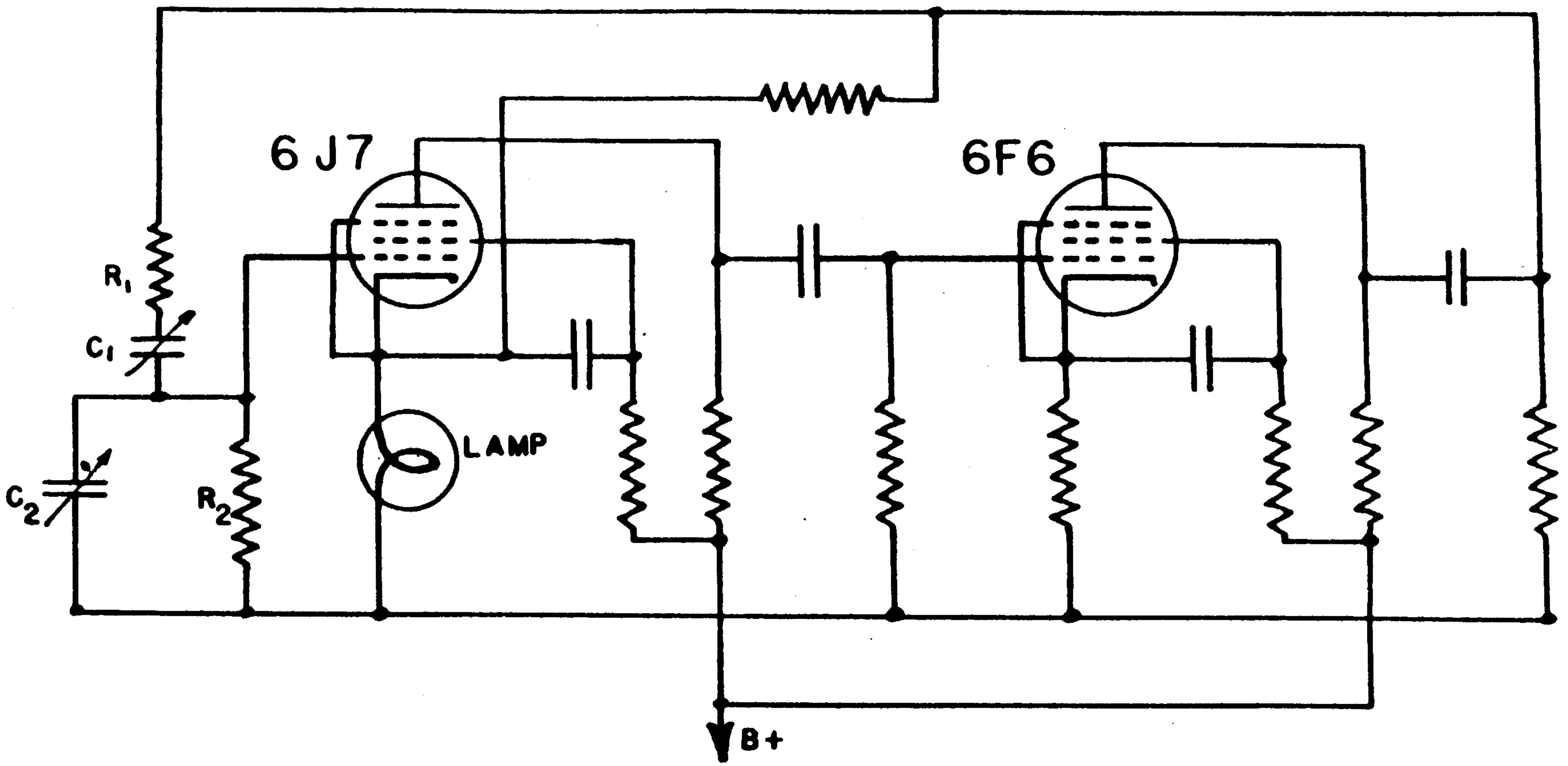
The last requirement, an amplitude-limiting device that will not introduce distortion, is more difficult to achieve. It is well known that the gain of an amplifier with negative feedback is $1/\beta$, providing $A\beta$ is large compared to 1. Thus if a resistance whose value increases with the current through it is used as part of the negative feedback network, the gain of the amplifier may be made to decrease with an increase in the input voltage. If an amplifier of this type is used as part of the oscillator, it can be adjusted so that oscillations will just start. As the oscillations build up, the gain of the amplifier will be reduced, thus reducing the tendency to oscillate and causing the amplitude of oscillations to reach a stable value. If this value is low enough, the tubes will operate class A, and no serious distortion will be introduced. Furthermore, any distortion that is produced, due to the non-linear characteristics of the tubes, will be reduced by a factor of $A\beta$ by the action of the negative feedback.

For the variable resistance, a small tungsten lamp may be used. It is a well known property of such lamps that as the current through them increases, the filament warms up, thereby increasing the lamp resistance. Figure 2 shows how the resistance of a 110 volt, 6 watt, tungsten lamp changes with the current through it. It may be seen that the maximum rate of change of resistance is when the load current is less than 20 milliamperes, and so to get maximum effect, the lamp should be operated in this region. In Fig. 3 is shown a complete diagram of the oscillator. The negative feedback is applied from the plate of the output tube to the cathode of the input tube. The lamp is placed from cathode to ground, so as to increase the feedback and reduce the gain of the amplifier as the oscillations build up.

The only requirement placed on the lamp is that it be operated at such a temperature that the time rate of change of cooling be small compared to half the period of the lowest frequency. As the radiation is proportional to the fourth power of the absolute

LAMP RESISTANCE





Circuit Diagram of Resistance Capacity
Oscillator

temperature, and as most of the energy is lost through radiation, this requirement may be easily met by not operating the lamp at too high a current. Under these conditions, the life of the lamp should be almost infinite.

The disadvantage of using a diode amplitude control is that it introduces distortion at some part of the cycle. If the conventional A.V.C. system is used, instability of oscillations result. The time delay that is inherent in such a circuit permits the amplitude of oscillation to increase to too large a value, and then the action of the A.V.C. suddenly blocks all oscillation. This leads to intermittent oscillations with a period dependent on the time delay of the A.V.C. system. It might be possible to design an A.V.C. system in which this difficulty was overcome, but the simplicity of the lamp circuit would preclude its use.

Some care must be taken in the design of the amplifier to minimize phase shift and insure stability. Consideration should be given to the physical layout of the parts to reduce stray capacities and insure satisfactory high frequency response. The effect of too large a phase shift will be to shift slightly the upper end of the high frequency scale, with the result that this range will fail to track with the other frequency ranges and cause an error in the calibration. At the low frequency end, there will be the same difficulty with phase shift, and so sufficiently large coupling condensers should be used.

III EXPERIMENTAL RESULTS

A resistance capacity oscillator was constructed and tested to determine whether it were practical. It was decided that the most practical frequency range to cover would be the range from 20 to 20,000 cycles. The variable condenser was four gang, 410 mmfd. per section, and operated with two gangs in parallel for each of the tuning condensers. To cover the desired frequency range, it was necessary for the fixed resistances to be 10 megohms for the low range, 1 megohm for the middle range, and 0.1 megohms for the high range. As these resistances were so high, it was necessary to use selected and matched carbon resistors. The general circuit was that shown in Fig. ~~2~~, 3 with the exception that the tuning resistances were arranged to that they would be changed by a gang switch.

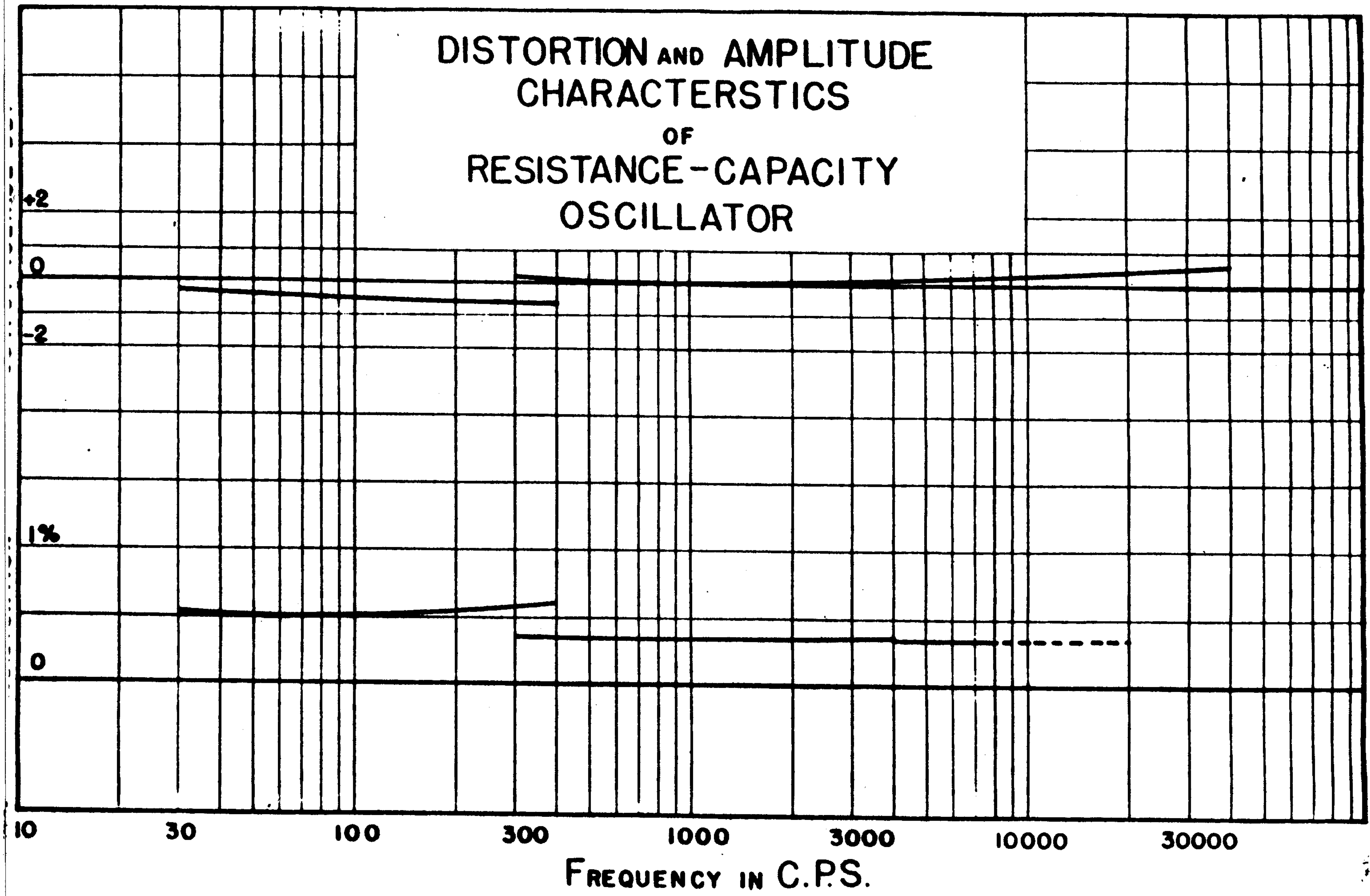
The factors that determine whether an oscillator is suitable for laboratory use are its frequency stability, its accuracy of calibration, its harmonic distortion, and its constancy of output over the desired frequency range.

The stability of the oscillator was checked by varying the supply voltage over a wide range and then determining the percentage change in frequency. When the supply voltage was varied ± 20 per cent, the maximum frequency change at 100 cycles was only 0.2 per cent. As compared to a beat-frequency oscillator, this is quite satisfactory, for at this frequency under similar conditions a beat-frequency oscillator might change as much as ± 5 per cent. It was also found that the frequency ranges would be made to track to within ± 1 per cent. If suitable resistances are used, they may be expected to hold their value to within ± 2 per cent over long periods of time. These facts combine to insure good frequency stability and accuracy of calibration under all operating conditions.

The harmonic content of the wave was measured at different frequencies by means of a General Radio wave analyzer. A characteristic curve of distortion vs. frequency is shown in Fig. 4. It may be seen that at all frequencies the distortion is less than 0.5 per cent of the fundamental. For most work this distortion may be considered negligible.

If the variable condensers are properly adjusted so that the ratio of the two capacities is the same over the full range of the condenser, the output can be held to within ± 1 db. from 20 to 20,000 cycles. The output voltage as a function of frequency is also plotted in Fig. 4.

Some investigation was made to determine the maximum and minimum frequency limits. There is a considerable demand for an oscillator that will operate in this frequency range, but there are two main



DISTORTION AND AMPLITUDE
CHARACTERSTICS
OF
RESISTANCE-CAPACITY
OSCILLATOR

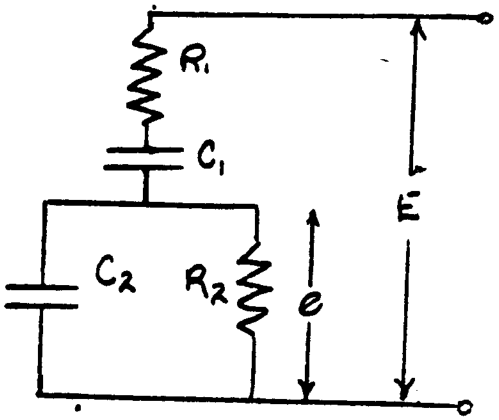
difficulties. In the first place, either very large resistances must be used, with insulation resistance or input impedance of the tube as a limiting factor, or a very large variable condenser must be obtained. The second limiting factor is the ballast lamp, for if this lamp changes its resistance during a half-cycle, distortion will result. Measurements were actually made to determine the wave-form of a resistance-capacity oscillator at 8 cycles, and the distortion was found to be less than 1 per cent. The distortion was measured by the use of a photographic oscillogram on which was performed a graphical harmonic analysis.

The upper frequency limit is determined by the frequency response of the amplifier. The problem, then, is the construction of a television amplifier that may be adapted to use as part of the oscillator. With a suitable design, the maximum usable frequency should be in excess of 1 mc. Mr. L. Jeffers has found that with sufficient care in the design of the amplifier, oscillations could be obtained up to about 5 mc. However, at this frequency there was no indication of the stability or of the harmonic content.

IV CONCLUSIONS

A resistance-capacity oscillator of the type just described should be well suited for laboratory service. It has the ease of handling of a beat-frequency oscillator and yet few of its disadvantages. In the first place the frequency stability at low frequencies is much better than is possible with the beat-frequency type. There need be no critical placements of parts to insure small temperature changes, nor carefully designed detector circuits to prevent interlocking of oscillators. As a result of this, the overall weight of the oscillator may be kept at a minimum. An oscillator of this type, including a 1 watt amplifier and power supply, weighed only 18 pounds, in contrast to 93 pounds for the General Radio beat-frequency oscillator of comparable performance. The distortion and constancy of output compare favorably with the best beat-frequency oscillators now available. Lastly, an oscillator of this type can be layed out and constructed on the same basis as a commercial broadcast receiver, but with fewer adjustments to make. It thus combines quality of performance with cheapness of cost to give an ideal laboratory oscillator.

V APPENDIX



$$Z_1 = R_1 + \frac{1}{j\omega C_1}.$$

$$Z_2 = \frac{\dfrac{R_2}{j\omega C2}}{R_2 + j\omega C_2R_2} = \frac{R_2}{1 + j\omega C_2R_2}.$$

$$\frac{e}{E} = \frac{Z_2}{Z_1 + Z_2}.$$

$$= \frac{\dfrac{R_2}{1 + j\omega C_2R_2}}{\dfrac{R_2}{1 + j\omega C_2R_2} + R_1 + \dfrac{1}{j\omega C_1}}.$$

$$= \frac{R_2}{R_1 + R_2 + \dfrac{C_2R_2}{C_1} - \dfrac{1}{j\omega C_1}(R_1R_2C_1C_2\omega^2 - 1)}$$

Now if resonance is defined as $(e/E)_{max}$, we find the resonant frequency, $\omega_o = \dfrac{1}{\sqrt{R_1R_2C_1C_2}}$. If we demand that $R_1C_1 = R_2C_2$.

Then,
$$\frac{e}{E} = \frac{R_2}{2R_1 + R_2 + j\dfrac{\omega}{\omega_o}R_1\left(1 - \dfrac{\omega_o^2}{\omega^2}\right)}.$$

At resonance,
$$\frac{e}{E} = \frac{R_2}{2R_1 + R2}.$$

From analogy with the L, C, R, circuit,

$$C_o = \frac{R_2}{2R_1 + R_2}.$$

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