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LC Oscillators and their Frequency Stability

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The rapid development of quartz-crystal manufacture during the war somewhat reduced the use of tuneable LC oscillators and may even have given rise to the opinion that these oscillators have lost most of their importance. The experience of the four post-war years indicates that this conclusion was incorrect, that the stable LC oscillator retains its place beside the crystal in the first stages of broadcast transmitters, and that it is irreplaceable in wavemeters, signal-generators and receivers.

The demands placed on the stability of these types of oscillators increased as compared with pre-war times, especially for transmitters and oscillators for measuring instruments. Their design, which until now has been a question of trial and error, must therefore be put on a firm theoretical basis. During recent years a number of circuits have appeared solving the problem of stability by different means (Clapp, Lampkin, Seiler, etc.). These circuits, which have found popularity among amateurs, are, however, seldom used in industry, mainly because of the narrow range over which good tuning can be achieved. In addition, no general theory has yet been given which would permit an objective comparison with regard to the attainable stability, thereby enabling the selection of a suitable circuit for the purpose.

The aim of this article is to give the basic requirements for the design, and a general mathematical analysis, of oscillators with an eye to the frequency stability; to derive practical rules for the design and calculation of stable LC oscillators; to evaluate the existing circuits; and, lastly, to describe new circuits and their practical construction.

Those oscillators having a frequency ratio of 2 : 3 permit a precision of frequency adjustment of 0.002% while their frequency stability is at least of the same order. Detailed results of the measurements are given below.

1. INDIVIDUAL CAUSES OF INSTABILITY, BASIC FACTS AND CONCEPTS

The frequency of a tuneable oscillator should be a single valued function of the tuning element (e. g. tuning condenser) setting. The frequency of normal oscillators is, of course, affected by a whole number of other factors, e. g. supply voltage, temperature, valve replacement, etc. Variations in these factors have to be reduced to a minimum for stable oscillators. The above assert themselves independently, and so an oscillator, which may be very stable as regards changes in the supply voltages can, on the other hand, be very unstable as regards changes in temperature. We must, therefore, pay special attention to each of these questions, for thereby we can obtain rules for the proper design. The table below is a summary of causes of frequency changes and the necessary preventive steps.

A more detailed account of design, principles especially in regard to the design of coils and condensers, follows.

Cause of unwanted frequency change	Domain	Relative frequency change df/f	Preventive steps
Mechanical vibration	tuning coil and condenser	up to a few %	mechanical stability, suitable design of coil and condenser, temperature compensation, etc.
Change in temperature	tuning coil and condenser	up to $1^0/_{00}/°C$	
Change in atmospheric pressure	air condensers	up to 3×10^{-7}/mm Hg	hermetically sealed tuning circuits
Change in humidity		up to $1 \times 10^{-6}/1\%$ humidity	
Change in CO_2 of air		up to $2 \times 10^{-6}/1\%$ CO_2	
Ageing of materials	tuning coil and condenser	up to a few %	do not use organic insulating materials
Change of valves	valves	up to a few %	suitable circuits and/or stabilised power supplies
Change of supply voltages		up to a few $^0/_{00}$	
Valve vibrations		up to a few $^0/_{00}$	

2. MECHANICAL DESIGN OF TUNING CIRCUIT

The coils of a stable oscillator must have a stable mechanical design and their inductance should be as possible independent of temperature and ageing of materials. From an electrical point of view, the Q should be the highest possible, while the self-capacity does not have to be kept low. Perhaps the best of all existing designs are those utilising ceramic formers with deposited silver windings. Nearly equally good results can be obtained by winding bare solid copper wire at a temperature of 80° to 90° C (e. g. over a suitable heating element) into grooves on a ceramic former, which, after fastening the ends, can be left to cool. On cooling, the wire contracts and is strained, thereby following only the thermal expansion of the ceramic former which for the normal temperatures is very small. In this way we obtain coils with a cyclic thermal coefficient $\frac{dL}{dt} \doteq 6$ to $8 \,.\, 10^{-6}$, i. e. after repeated heating and cooling there is no change of inductance. The high Q is obtained by making the coil short and with a relatively large diameter ($0.3 \leq l/D \leq 0.6$) and by choosing the diameter of the wire to be approx. 0.6—0.7 of the winding pitch leaving a comparatively small distance between wires. The shield has to be of rigid design and its diameter at least twice that of the coil.

The tuning condenser requires the same attention as the coil but the constructional requirements depend on the frequency ratio needed. In the extreme case when a ratio of 2 : 3 was required without switching, with a precision of adjustment of one part in 50,000, it was necessary to design a condenser with axial and radial play less than 0.001 mm and a ground worm gear of 1 to 160 to permit accurate adjustment. Generally, however, this sort of solution is not economical and we try to do with less expensive parts. For example, better quality variable condensers with large air gaps have a stability of the order of one part in a thousand, i. e. chance variation of capacity over longer periods is less that one thousandth of their maximum capacity. Normal tuning condensers used in broadcast receivers have a stability of one part in 500.

If we want to use such a condenser (e. g. stability of one part in 500) to tune an oscillator with a frequency stability of 5×10^{-5} then we have to use such a circuit that the tuning range $f_{min} : f_{max}$ covered by the said condenser will be only 1 : 1.025, i. e. the overall relative frequency change $\frac{\Delta f}{f} = \frac{1}{40}$. The tuning condenser error of 1/500 is then reduced to $1 : 500 \times 40 = = 5 \times 10^{-5}$. This we achieve by adding fixed condensers or by connecting the tuning condenser to a tap on the coil. For larger frequency ratios than 1 : 1.025 we either switch the coil taps or the padding condensers. The fixed condensers are best chosen from among the larger ceramic types (test voltage 2 to 3 kV).

Very exacting requirements are put on the coil tap or fixed condenser switch. As in the interest of short leads and mechanical rigidity, this switch is generally placed near the coil, it is important that the points of contact should be well defined and that the whole switch should be electrically and mechanically stable. These requirements are best satisfied by a cam-operated switch with ceramic insulation or a robust ceramic wafer-switch. Here too, we try to avoid organic insulating materials (bakelite, bakelite bonded paper, styrene, etc.) which over longer periods change their degree of polymerisation and therefore their dielectric constant, power factor and even dimensions.

The coils, condensers and switch are the most important parts which affect the frequency stability regardless of the circuit used. As a rule we place these parts in a common shield. It is very advantageous to cover this shield with a thermal insulating material (felt or cork 5 to 10 mm thick), thereby protecting the tuning elements from sudden changes in temperature. This is especially important when using thermal compensation, which fulfils its purpose only when all temperature changes occur at the same time and throughout the whole tuning circuit.

The above paragraphs describe the conditions of design of stable tuning circuits. The second part discusses the causes of frequency instability which originate in the valve. The valve used in the oscillators is connected to the tuning circuit and its internal capacity, lead inductance, and internal resistance are, therefore, part of that circuit thereby affecting the frequency. The grid-cathode capacity, for example, varies with the space charge as much as $\pm 10\%$ depending on variations in the supply voltages, causing an indirect influence on the frequency. Likewise the other internal capacities vary from valve to valve up to $\pm 10\%$. The effect of these variations on the frequency has to be minimised by a proper choice of external circuit.

3. CIRCUIT OF OSCILLATOR

To get an objective measure for different oscillator circuits, we have to get a common starting point in the form of an equivalent circuit valid for all types of oscillator circuits. If we limit ourselves to oscillators with negligible transit time effects, then we can use the equivalent circuit shown in Fig. 1. This circuit is satisfactory for all usual feed-back oscillators and even for cases like the dynatron and the cathode-follower oscillator, where the input and output terminals of each four-pole in Fig. 1 are joined, thereby changing the four-pole into a two-pole with equivalent properties.

The equivalent circuit shown in Fig. 1 is an oscillator represented by interconnecting two four-poles, the upper one being the active network, representing the valve, while the lower is passive and represents the tuned circuit.

Let us introduce the following notation:

Z_1 = input impedance of valve (mainly grid-cathode capacity)
Z_2 = output impedance of valve (mainly anode-cathode capacity)
G_m = mutual conductance
I_1 = input current into grid of valve
E_1 = input voltage at grid of valve
I_{2s} = short circuit output current of valve
E_{20} = open circuit output voltage of valve
I_2 = output current of valve in load Z_2'
E_2 = output voltage of valve across load Z_2'
Z_2' = input impedance of tuned circuit (on anode side)
Z_1' = output impedance of tuned circuit (on grid side)
Z_M = mutual impedance of tuned circuit (see below)
E_{10} = open circuit output voltage of tuned circuit (on grid side)
I_{1s} = short circuit output current of tuned circuit
R_0 = parallel impedance of tuned circuit at resonance
E_0 = voltage on tuned circuit.

All the above quantities (except R_0) are regarded as complex.

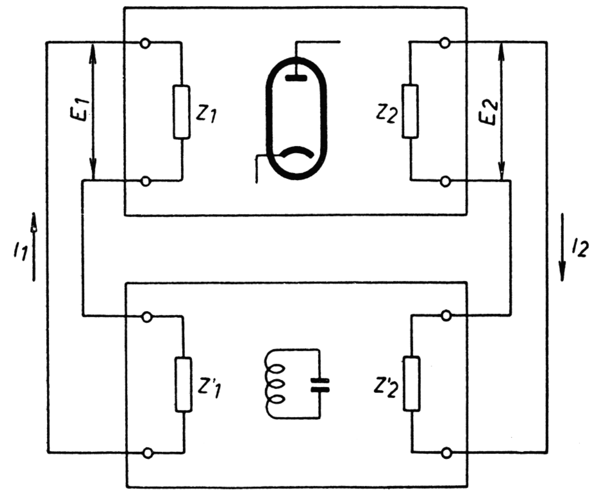

Fig. 1

We can now describe the properties of the two four-poles by the following relations:

$$Z_1 = \frac{E_1}{I_1}, \tag{1}$$

$$Z_2 = \frac{E_{20}}{I_{2s}}, \tag{2}$$

$$G_m = \frac{I_{2s}}{E_1}, \tag{3}$$

$$G_m = a e^{j\alpha} \tag{4}$$

Equation (4) is a general way of writing the mutual conductance where α is the phase-angle by which the anode current lags behind the grid voltage as a result of the finite transit time of the electrons in the valve.

In a similar way we define the properties of the second four-pole. If we assume that all the losses of the circuit are concentrated in the parallel resistance R_0, and that the transformations from the anode to the tuned circuit and from the tuned circuit are loss-less, a condition met in practice, then the well-known impedance transformations are valid:

$$E_0 = E_2 \sqrt{\frac{R_0}{Z_2'}}, \tag{5}$$

$$E_{10} = E_0 \sqrt{\frac{Z_1'}{R_0}}, \tag{6}$$

from which it follows that

$$E_{10} = E_2 \sqrt{\frac{Z_1'}{Z_2'}} \tag{7}$$

and since

$$E_2 = I_2 Z_2' \tag{8}$$

we obtain by substituting (8) into (7)

$$E_{10} = I_2 \sqrt{Z_1' Z_2'}. \tag{9}$$

The geometric mean of the impedances Z_1' and Z_2' we can call the mutual impedance Z_M and write symbolically:

$$Z_M = Z_1' Z_2' = b e^{j\beta}, \tag{10}$$

where b represents the magnitude and β the phase-angle of the impedance.

For the passage from the first to the second four-pole the following relations hold:

$$I_2 = I_{2s} \frac{Z_2}{Z_2 + Z_2'}, \tag{11}$$

where the fraction can be expressed symbolically by:

$$\frac{Z_2}{Z_2 + Z_2'} = c e^{j\gamma} \tag{12}$$

and finally

$$E_1 = E_{10} \frac{Z_1}{Z_1 + Z_1'}, \tag{13}$$

$$\frac{Z_1}{Z_1 + Z_1'} = d e^{j\delta}. \tag{14}$$

The quantities E_1, I_{2s}, I_2, E_{10}, E_1 are, therefore, cyclically inter-connected by equations (3), (11), (9), (13), their mutual substitution furnishing conditions for oscillation:

$$abcd = 1, \tag{15}$$

$$\alpha + \beta + \gamma + \delta = 0°. \tag{16}$$

This general criterion of oscillation may be simplified in practice as the following relations generally hold:

$$Z_1' \ll Z_1, \tag{17}$$

$$Z_2' \ll Z_2 \tag{18}$$

and therefore

$$I_2 = I_{2s}, \tag{19}$$

$$E_1 = E_{10}, \tag{20}$$

$$c = d = 1, \tag{21}$$

$$\gamma = \delta = 0°. \tag{22}$$

The criterion of oscillation then is:

$$ab = 1, \tag{23}$$

which after substituting from equations (4) and (10) yields

$$\sqrt{Z_1' Z_2'} = \frac{1}{G_m}. \tag{24}$$

Let us now examine the change of frequency caused by a change of internal capacity of the valve. This we shall do on the basis that by resonant transformations the ohmic and reactive impedances are transformed equally. A change, ΔC_1, in the input capacity connected to the impedance Z_1' manifests itself in a detuning caused by an equivalent capacity ΔC_0 in the tuned circuit of dynamic resistance R_0 so that:

$$\frac{\Delta C_1}{\Delta C_0} = \frac{R_0}{Z_1'} \tag{25}$$

if the tuning condenser is C_0 then

$$\frac{\Delta f}{f} = \frac{\Delta C_0}{2\, C_0} \tag{26}$$

which after substituting for ΔC_0 from (25) yields

$$\frac{\Delta f}{f} = \frac{\Delta C_1 Z_1'}{2\, C_0 R_0}. \tag{27}$$

The greater the impedance Z_1', the greater is the change of frequency. The same considerations hold for changes in capacity ΔC_2 and impedance Z_2'. For minimum frequency changes caused by changes in the capacities C_1 and C_2, when $Z_1' Z_2'$ is given in (24), the optimal solution is:

$$Z_1' = Z_2' = Z_M = \frac{1}{G_m}. \tag{28}$$

From the above and further from equations (5) and (6) we get

$$E_1 = E_2, \tag{29}$$

i. e. the grid voltage is equal to the anode voltage. This results in the valve working with a low efficiency, which in low-power stable oscillators is of little importance.

An oscillator with impedances designed according to equations (28) has, therefore, the highest possible stability with regard to changes in internal capacities of the valves. We shall now estimate the frequency change caused by a change of 1 pF in either internal capacity, the highest value likely to be met with in usual valves. Starting from equation (27)

$$\frac{\Delta f}{f} = \frac{\Delta C_1 Z_1'}{2\, C_0 R_0} \tag{27}$$

substituting for Z_1' from (28) and the well-known value for R_0

$$R_0 = \frac{Q}{\omega\, C_0} \tag{30}$$

we get

$$\frac{\Delta f}{f} = \frac{\Delta\, C_1 \omega}{2\, G_m Q}. \tag{31}$$

The relative change of frequency is smaller, with higher circuit Q and with higher mutual conductance of the valve, and for a given ΔC_1 it is proportional to the frequency.

We therefore work with high slope valves and try to obtain a Q as high as possible. Another important point demonstrated by equation (31) is that the stability is independent of $\frac{L}{C}$ of the tuned circuit. We can therefore choose $\frac{L}{C}$ so as to obtain a simple mechanical design.

If we re-write equation (31) so as to be able to substitute practical units, we get after putting $\Delta C_1 = 1$ pF

$$\frac{\Delta f}{f} \doteq \frac{1}{\lambda Q G_m}, \tag{32}$$

where λ is wavelength in metres and G_m the mutual conductance in mA/V (millimhos). For example, when using a valve with $G_m = 5$ mA/V and a tuned circuit of $Q = 100$ we get for $\lambda = 1000$ m

$$\frac{\Delta f}{f} = 2 \times 10^{-6}.$$

4. A CRITICAL REVIEW OF EXISTING CIRCUITS

Criterion (28) derived above means that the highest possible stability regarding the internal capacities of the valves can be achieved by connecting the anode and grid to points of the tuned circuit of as low an impedance as will still maintain oscillation. This criterion, independently discovered by a number of authors, was realised in different ways as shown in the diagrams. The oscillator of Gouriet which has been in operation at the B. B. C. since 1938 (as stated by E. K. Sandeman in his *"Radio Engineering"*, 1947), was not published before this date and was re-discovered by J. K. Clapp in 1946 (see Fig. 2). The circuits by Seiler (QST 1941) and Lampkin (Proc. IRE 1939) follow the same idea. It seems, therefore, that if we keep, with their designs, to the rules contained in equations (5), (6) and (28) we must arrive at the same results as regards stability.

This reasoning is correct with regard to a single-frequency for which the calculation is carried out. But if the frequency is varied, conditions change abruptly and different oscillators give very different results. We shall try, by an example, to follow these conditions in the circuit of Gouriet-Clapp (Fig. 2). Let C_0 be the tuning condenser, C_a and C_g the anode-cathode and grid-cathode capacities, respectively. Further, let us assume that the Q is nearly constant over the tuned frequency range and that $C_a \doteq C_g$; we can then write

$$R_0 = \frac{Q}{\omega C_0}, \tag{30}$$

$$Z_1' = Z_2' = R_0 \left(\frac{C_0}{C_a}\right)^2, \tag{33}$$

$$G_m = \frac{\omega C_a}{Q} \frac{C_a}{C_0} \tag{34}$$

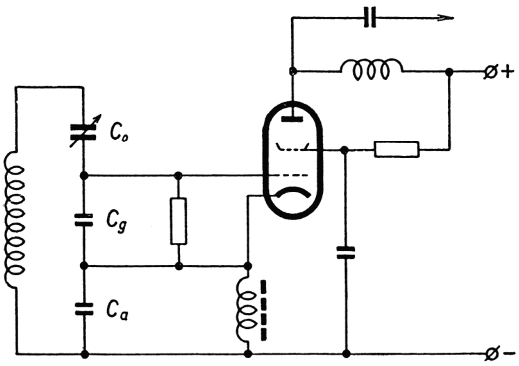

Fig. 2

and because

$$C_0 \doteq \frac{k}{\omega^2} \tag{35}$$

we can substitute into (34) and write

$$G_m \doteq \text{const.}\ \omega^3. \tag{34a}$$

We see that the mutual conductance necessary to maintain oscillations in the Clapp oscillator is proportional to the third power of the frequency. The consequence is that the mutual conductance necessary to maintain oscillations when tuning the oscil-

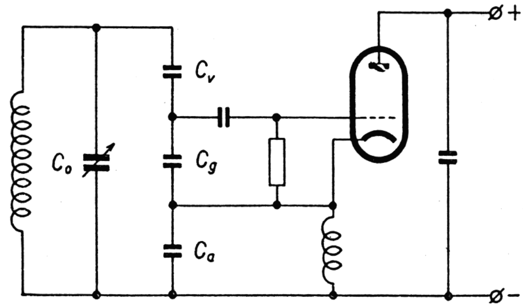

Fig. 3

lator towards longer waves decreases; for constant mutual conductance the amplitude, and therefore also the grid bias, increases until the valve operates in class "C" and the dynamic conductance decreases to the needed value. When tuning towards shorter waves the necessary conductance rises and the amplitude decreases until oscillations stop. Even though Clapp's circuit has the advantage of simplicity, it can only be used for operation on fixed frequencies or at the most over narrow bands (max. about 1 : 1.2).

The circuits due to Lampkin (Fig. 4) and Seiler (Fig. 3) behave quite differently. The two circuits are equivalent, the only difference being that Seiler uses a capacitive and Lampkin an inductive voltage divider (the tuning coil) for impedance transforma-

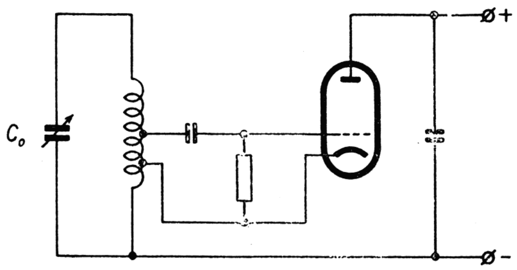

Fig. 4

tion. Let us calculate the dependence of mutual conductance on the frequency for the circuit due to Seiler which has, moreover, the advantage that when operating in class "C" or "B" its capacitive divider effectively short-circuits higher harmonics to ground. Let C_0 again be the tuning condenser, C_a and C_g the anode-cathode and grid-cathode capacities respectively and let C_v be the condenser from the grid to the "live" side of the tuned circuit. If we assume that $C_0 \gg C_v$ and $C_a = C_g \gg C_v$ we can write:

$$R_0 = \frac{Q}{\omega C_0}, \tag{30}$$

$$Z_1' = Z_2' = R_0 \left(\frac{C_v}{C_a}\right)^2, \tag{36}$$

$$G_m \frac{\text{const}}{\omega}. \tag{36a}$$

It can be seen that the mutual conductance is inversely proportional to the first power of the frequency. The amplitude dependence on frequency is reversed to that of Clapp's circuit but the change in amplitude is much less pronounced. This circuit can therefore be used for larger frequency ranges up to approx. 1 : 1.8.

The next circuit, known as the cathode follower oscillator, in short CFO (see Fig. 7), can also achieve a comparatively high stability when connected to the tuned circuit at a point of lowest possible impedance. For its operation the following relations hold. If:

R_k = common cathode resistor

G_m = mutual conductance, equal for both triodes

$E_{g1} = E_{a2}$ AC voltage on grid of first and anode of second triode

I_{a2} = AC component of anode current of second triode

E_k = AC voltage on common cathode

and if

$$G_m R_k \gg 1,$$

$$E_k \doteq \tfrac{1}{2} E_g,$$

$$I_{a2} \doteq \tfrac{1}{2} E_{g1} G_m$$

and for this current to produce the voltage E_{g1} (condition of oscillation) the impedance at the point of connection of the valve

$$Z = \frac{E_{g1}}{I_{a2}} = \frac{2}{G_m}.$$

The impedance is obviously twice that calculated for the previous cases and the same as if we had used valves with halved mutual conductances. Because the condition of stability equation (28) is valid for this case too

$$\frac{df}{f} = \frac{1}{\lambda Q G_m}, \tag{28}$$

we get for equal mutual conductance half the stability as in the previous oscillator. Its advantage, of course, is a certain simplicity in design of the tuned circuit. When tuning this oscillator over larger frequency ranges, the amplitude will change similarly as in the oscillator due to Seiler, because of the constant transformation of dynamic resistance. The amplitude, therefore, rises proportionately with the frequency.

The development of stable oscillators in Czechoslovakia progressed independently and without technical information about developments in the West. In 1945, the firm Radioslavia developed a stable oscillator which successfully combined the

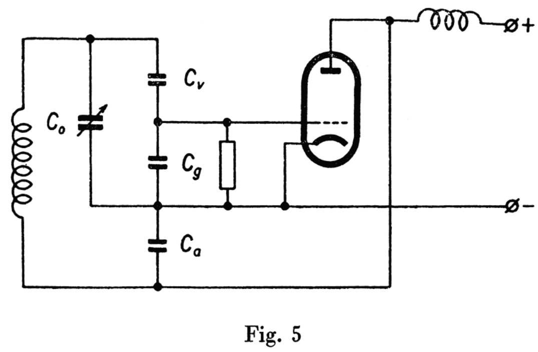

Fig. 5

properties of the two above-mentioned circuits and maintained a comparatively constant amplitude over a wide frequency range. This circuit (Fig. 5) has been in practical operation since 1946 in code transmitters of the Czechoslovak Post Office and has an operating frequency stability of 5×10^{-5}, although oscillating on a relatively short wave (130—180 m).

We met with the same fate as Gouriet; our circuit was discovered independently and described just a year ago by the Italian O. Landini in the journal Radio Rivista. The latter, however, worked only experimentally and to the extent that he gives theoretical calculations at all, he starts from false premises. We shall therefore give an outline of the calculations.

Let us assume the same symbols C_a, C_g, C_v, and C_0 as in the previous example and further let $C_v \ll C_0$, $C_g \gg C_v$ and $C_a \gg C_0$; we can then write

$$G_m = \frac{1}{\sqrt{Z_1' Z_2'}}, \qquad (24)$$

$$Z_1' = R_0 \left(\frac{C_v}{C_g}\right)^2, \qquad (37)$$

$$Z_2' = R_0 \left(\frac{C_0}{C_a}\right)^2, \qquad (38)$$

$$R_0 = \frac{Q}{\omega C_0} \qquad (30)$$

substituting into (24) we get

$$G_m = \frac{\omega}{Q \frac{C_v}{C_g C_a}}. \qquad (39)$$

Since, with the coil used, the Q increased moderately with frequency, the necessary mutual conductance, and thus also the amplitude, is constant.

The values of the condensers C_v, C_g and C_a have to be determined so that equation (28) will be satisfied for centre frequency of the range, i. e.

$$\frac{1}{G_m} = \frac{Q}{\omega_c C_{0c}} \cdot \left(\frac{C_{0c}}{C_a}\right)^2 = \frac{Q}{\omega_c C_{0c}} \left(\frac{C_v}{C_g}\right)^2 \qquad (40)$$

When actually designing this oscillator we proceed in the following manner:

Let us say the oscillator has to have a frequency range of 1700—2000 kc/s and a stability of 10^{-4}; we first decide on the tuning condenser. We can either use a specially designed condenser which of course would be considerably laborious and expensive but which would, without switching, tune the whole range with sufficient precision or we can use a condenser of normal production. Then, of course, it is necessary to sub-divide the frequency range and use a switch to obtain the required precision; e. g., to use a 100 pF circular plate condenser (when tuning such a narrow range logarithmic plates are of no advantage) with an estimated stability of one part in 500, then its maximum tuning range to get a resultant stability of 10^{-4} will be:

$$\frac{f_{\max}}{f_{\min}} = 1 + \frac{500}{10000} = 1.05.$$

If we want to cover the range of 1700—2000 kc/s, i. e. 1 : 1.17, we can sub-divide it into four bands with a tuning range of 1 : 1.05 with a small overlap, e. g. 1690—1775 kc, 1770—1860 kc, 1850—1940 kc and 1930—2020 kc.

To a tuning range of $f_{\max} : f_{\min} = 1.05$ corresponds a tuning condenser with

$$\frac{C_0 \max}{C_0 \min} = \left(\frac{f \max}{f \min}\right)^2 = 1.1,$$

i. e. the tuning capacity has a variation $C + \Delta C = 1.1 C_0 \min$. The difference $\Delta C = 0.1 C_0$ min. corresponds to the tuning condenser capacity of 100 pF, the fixed minimum condenser then is

$$C_0 \min = 10 \Delta C = 1000 \text{ pF}$$

and is best made of Calit or Tempa S, part of which can be of Condensa and can serve as thermal compensation. The inductance we calculate from $C_0 \min = 1000$ pF and the maximum frequency 2020 kc/s,

$$L = \frac{25{,}300}{Cf^2} = 6.2\ \mu\text{H},$$

for which we can use our normal ceramic form of 45 mm diameter and pitch of 1 mm. According to the known formula we find $\frac{l}{D} = 0.21$, i. e. 9.5 turns. The coil is wound with a wire of 0.7 of the pitch, that is, a diameter of 0.7 mm according to the method given above. The other three ranges are covered by switching further 100 pF condensers into the circuit.

The parallel impedance of the circuit of a centre frequency of 1850 kc/s will be

$$R_0 = \frac{Q}{\omega C_0}. \qquad (30)$$

If we assume the Q to be 100 and with a capacity $C_0 = 1200$ pF, we get

$$R_0 = 7200\ \Omega.$$

To fulfil the optimum condition of stability (28) with an EF 50 of 5 mA/V operating conductance we have:

$$Z_1' = Z_2' = \frac{1}{G_m} = 200\ \Omega.$$

The impedance transformation ratio is, therefore, $R_0/Z_{12}' = 36 : 1$, by which the voltage transformation ratio is fixed and also the ratio of condensers which is $\sqrt{36 : 1} = 6 : 1$.

We therefore get:

$$\frac{C_a}{C_0} = \frac{C_g}{C_v} = 6 : 1,$$

$$C_a = 6\, C_0 = 7200 \text{ pF}.$$

and by choosing $C_v = 100$ pF we get $C_g = 600$ pF.

One must not forget, of course, that because of the necessary assumptions (e. g. Q) these results will only be approximate, and in practice it will be necessary to adjust these values according to exact measurements.

The stability with respect to internal capacity changes will be, according to (32),

$$\frac{df}{f} = \frac{1}{\lambda Q\, G_m} = 1.25 \times 10^{-5},$$

i. e. for a change of internal capacity of 1 pF we get a change of frequency

$$1.85 \times 10^6 \times 1.25 \times 10^{-5} = 23 \text{ cps}.$$

The next circuit shown in Fig. 6 is similar to the previous one, the only difference being that the condenser C_a is divided into C_{a1} and C_{a2} between which the tuning condenser is connected. This circuit is a compromise between the previous circuit and that due to Seiler, and permits a constant amplitude in a still greater frequency range (up to

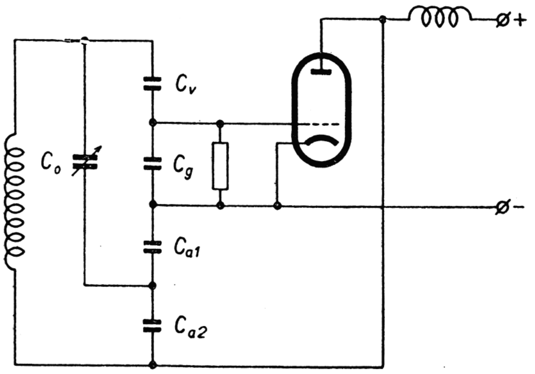

Fig. 6

1 : 2.5) which is of importance for wave meters and communication receivers. Its calculation is, of course, more involved, as we have to take into account the frequency dependence in the given frequency range of the Q of the coil used. The best method, therefore, is one of trial and error; choosing as a starting point these values of circuit parameters: $C_v = 0.1 C_0$, $C_g = C_{a1}$ we calculate in the same way as above, $C_{a2} = 10 C_0$. C_{a1} is adjusted finally so as to keep the amplitude of oscillation practically constant over the whole tuning range. Should the amplitude be too small, or should the circuit not oscillate at all, then we have to decrease both C_{a1} and C_g, and the reverse. The amplitude of oscillation should be adjusted to such a value that the anode current when oscillating is 60% of the quiescent current, which is the case only if there is no cathode bias resistor.

This bias should not be used, but rather the screen or anode voltage should be lowered so as not to endanger the valve when oscillation stops. The best valve for this purpose is, as was shown, a valve with a high mutual conductance. As the anode load impedance Z_2 is small (of the order of 100—500 Ω), the internal resistance is of no significance and it is all the same whether we use a triode or a pentode; only a high mutual conductance is of importance. It is further of advantage for the valve to have this high

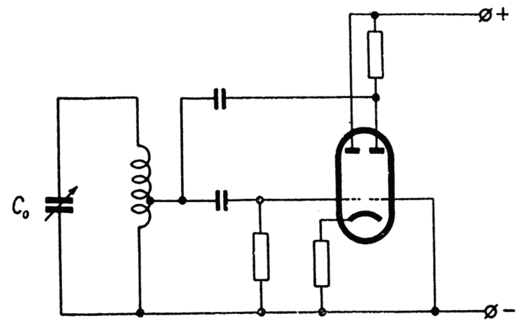

Fig. 7

conductance with a low anode current, for in this case the power delivered by the valve to the tuned circuit is only of the order of a few milliwatts, which does not cause the well-known "creeping" of frequency after switching on. This calls for using high-slope H.F. pentodes, e. g. EF50, EF14, etc. Good results can also be obtained by using the usual output valves EL12, EBL21, etc. with reduced screen grid voltage (100—140 V). These facts are, of course, valid for all types of oscillators described here.

The last circuit (shown in Fig. 8) uses a variable inductance which can be tuned, either by moving an iron core or a short-circuited turn, by a micrometric screw instead of a variable condenser. The frequency

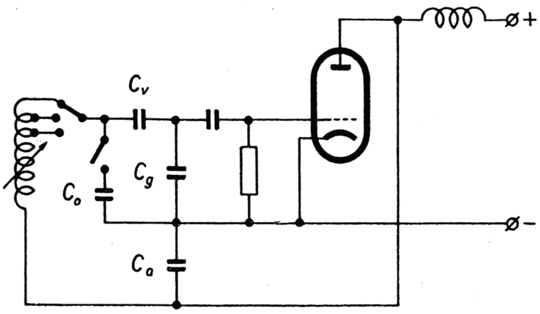

Fig. 8

range obtainable with an iron core is 1 : 1.1, that with a short-circuited turn is, because of the losses and hence necessarily looser coupling used, max. 1 : 1.05. By fixing the iron core to a micrometric screw we obtain great precision; in a concrete case, e. g., with a total travel of the core of 20 mm and a pitch of the micrometric screw of 1 mm, one division of the hundred division circular dial corresponds to a change in frequency of one part in 20,000. This component is, of course, considerably simpler and cheaper than a special tuning condenser designed to satisfy the same specifications.

When a greater tuning range than 1 : 1.1 is needed, we provide the coil with taps, switch condensers, or even both. In Fig. 8 the switched condenser is connected similarly to the tuning condenser in Fig. 5 which ensures a constant amplitude when switching this condenser into the circuit. The condensers C_v, C_a and C_g are dimensionally equal to those used in Fig. 5.

CONCLUSION

In the above article a survey has been made of the factors affecting the frequency stability of oscillators; mechanical and electrical conditions have been derived for the design and construction of oscillators with high frequency stability; a method of calculating the general oscillator with regard to its frequency stability has been given; causes of instability have been separated and defined; and a formula has been derived for the direct evaluation of electrical stability (defined as the relative change of frequency caused by a change of 1 pF in the internal capacitance of a valve).

A survey has also been made of existing circuits of modern stable low impedance oscillators, i. e. the impedances seen by the valve are as low as possible, their evaluation as regards attainable frequency stability; and amplitude versus frequency dependence when they are tuned over a given frequency band. When optimal frequency and amplitude stability is required, new circuits have been proposed which have been tested in practice and which are used in the construction of oscillators for broadcast transmitters at TESLA. The evaluation of these circuits and practical results are given.

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