APPENDIX A

THE ZERO PHASE-SHIFT OSCILLATOR WITH WIEN-BRIDGE CONTROL

General Application

Recent BBC designs of variable a.f. oscillators consist basically of a two-valve zero phase-shift maintaining circuit, the input and output of which are connected across opposite diagonals of a Wien bridge providing frequency and amplitude control. Such an arrangement is exemplified by the TS/9, PTS/10, PTS/12 and PTS/13. The principle of operation will be explained here with reference to the PTS/12.

A simplified circuit diagram of the PTS/12, is given in Fig. 9.6. The first two stages, comprising the maintaining network with Wien-bridge control, are redrawn in Fig. A.1. Each stage introduces a phase-shift between grid and anode of approximately 180 degrees, and the output from V2 is therefore nearly if not quite in phase with the input to V1. Without further examination, it will be clear that the following requirements must be fulfilled if oscillation is to occur:

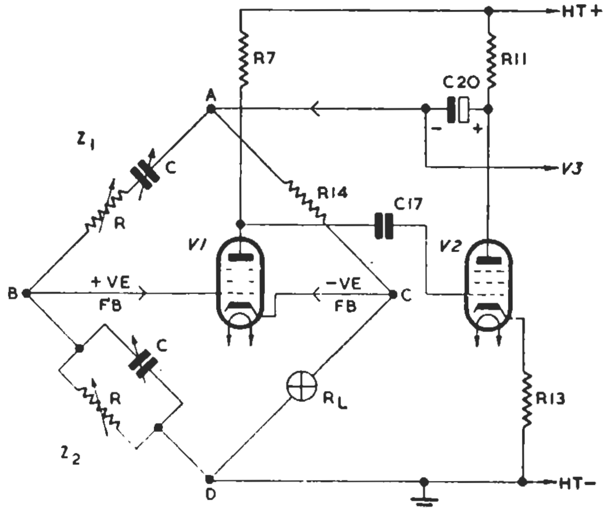

Fig. 9.1.1. PTS/12 Oscillation-maintaining Circuit with Wien-bridge Frequency and Amplitude Control

(1) Positive feedback must be applied via the bridge from V2 anode to V1 grid, the voltage fed back having a maximum value at some definite frequency.

(2) The loss introduced by the bridge must not exceed the gain obtainable from the valves in the maintaining circuit.

In practice, both requirements can easily be met by the circuit shown; the bridge then operates very near balance, and the balance conditions will therefore be derived.

Wien Bridge Network

Conditions for Balance

The four arms of the Wien bridge (Fig. A.1) comprise a series RC combination, Z_1, a parallel RC combination, Z_2, a fixed-value resistor R_{14} and a lamp with non-linear resistance R_L. The values of the resistive and capacitive elements R and C are variable, but in this application are kept equal in both arms of the bridge at all settings.

At balance,

$$\frac{R_{14}}{R_L} = \frac{Z_1}{Z_2}$$

Substituting the admittance, Y_2, which is the reciprocal of the impedance, Z_2:

$$\begin{aligned}\frac{R_{14}}{R_L} &= Z_1Y_2\\ &= (R-j/\omega C)\,(1/R+j\omega C)\\ &= 2+j(\omega CR-1/\omega CR)\end{aligned}$$

Separating the equation into its real and imaginary parts,

$$\frac{R_{14}}{R_L} = 2, \text{ and}$$

$$\omega CR - 1/\omega CR = 0.$$

Whence $$\omega^2 = \frac{1}{C^2R^2},$$

and since the frequency f is equal to $\omega/2\pi$,

$$f = \frac{1}{2\pi RC}$$

It follows that, providing R_{14} has twice the resistance of the lamp, balance occurs at a frequency $1/2\pi RC$.

Assume for the moment that the phase-shift through the maintaining amplifier is accurately zero between V1 grid input at B and V2 output at A ; the valves will then build up oscillations, but only at the frequency for which the phase of the feedback voltage applied at B is the same as that at A. The reason for the restriction is that any quadrature component possessed by the feedback voltage will be degenerative, since it cannot be reinforced by further amplification ; from another standpoint, an input component in quadrature with the output makes no contribution, when amplified, to the power required to replace the circuit dissipation.

Thus, the reactive branch of the Wien bridge alone would be capable of controlling the frequency of oscillation, and with zero phase-shift through the maintaining circuit, the oscillatory frequency would be $1/2\pi RC$. However, small changes in phase are likely to be caused by the coupling capacitors, and by other effects of minor importance. For regeneration to take place, a small phase-change might thus need to be introduced by the control network ABD, and the frequency of oscillation would depart slightly from that previously stated. This effect is minimised by the use of current negative feedback in the maintaining amplifier.

Amplitude Limitation

The argument contained in the preceding subsection is applicable irrespective of the presence of the resistive arms of the bridge R_{14} and R_L, although if these arms were absent V1 cathode would of course have to be earthed with respect to a.c. Since, however, the gain required from the maintaining amplifier is only about 10 db, some form of limiter is necessary to prevent the amplitude of oscillation from increasing until finally restricted by valve-characteristic curvature or other non-linear means. The addition of the resistive branch is a convenient method of providing the required amplitude limitation. It should be mentioned that, although the completed network ABDC takes the form of a bridge, under oscillatory conditions the voltage at point B in the reactive branch ABD always remains one-third that at A, both voltages being measured with respect to the earth-point D.

The voltage feedback at B is applied in a positive sense to V1 grid, whereas that at C is applied in a negative sense to V1 cathode. If the lamp resistance R_L were fixed at exactly half R_{14}, the bridge would be in balance, and the voltages fed back to points B and C would be numerically the same. Thus, no net signal would be applied between V1 grid and cathode, and oscillation could not occur. It is therefore necessary to arrange that, under operating conditions, R_L shall be *less* than half R_{14}.

The resistance of the lamp increases with the current passing through it. (This current includes not only that supplied through R_{14}, but also the cathode current of V1, the a.c. component of which contributes a measure of current feedback as distinct from the voltage feedback applied via R_{14}.) The change in lamp resistance with current causes the degree of unbalance in the bridge to vary as an inverse function of the oscillation level, and thus to stabilise the level at a value depending on the circuit design.

Application to Oscillator Control

In Fig. A.1, the diagonal corners of the bridge are labelled for reference A, B, C and D. A feedback voltage from V2 anode is applied between points A and D, the latter of which is at earth potential. Since the branch ACD, containing R_{14} and R_L, is purely resistive, there is no difference of phase between the voltage at C and that at A, measured with respect to the earth point D. When the bridge is balanced, the voltage at B must be precisely the same as that at C, both in magnitude and in phase ; from this fact two inferences are to be drawn.

Firstly, it has already been shown that for balance, R_L must be equal half R_{14}, so that with respect to earth, the voltage at C is one-third that at A. It can now therefore be stated that the voltage at B is also one-third that at A.

Secondly, since the voltages at B and C are equal not only in magnitude, but also in phase, the voltage at B must thus have the same phase as that at A.

It follows that the branch ABD divides the feedback voltage applied from V2 anode to V1 grid in the ratio of 3 to 1 without change of phase. The loss to be made good by the maintaining circuit, V1, V2, is 20.log 3, or 9·54 db. This is true, irrespective of the presence of the other branch ACD, always providing that the operating frequency remains at $1/2\pi RC$.

The important property of the network ABD is that it does in fact introduce zero phase-shift only at the single frequency $1/2\pi RC$. At any higher frequency, capacitive reactance decreases, and capacitive currents rise, causing the voltage at B to lag on that at A ; conversely, at any lower frequency, the voltage at B leads on that at A.

Any slight rise in level which may be caused by a change in external conditions increases the current through the lamp and brings the bridge nearer to balance, so that V1 input falls and the level drops back toward the stable value. Any slight fall below the stable level correspondingly reduces the lamp current; R_L thus decreases, and the degree of unbalance is increased, causing the level to rise again.

When stability is reached, the 10-db loss in ABD, plus the gain reduction due to the total negative feedback applied at C, must together equal the gain of the maintaining amplifier, V1, V2, with the feedback bridge network disconnected.

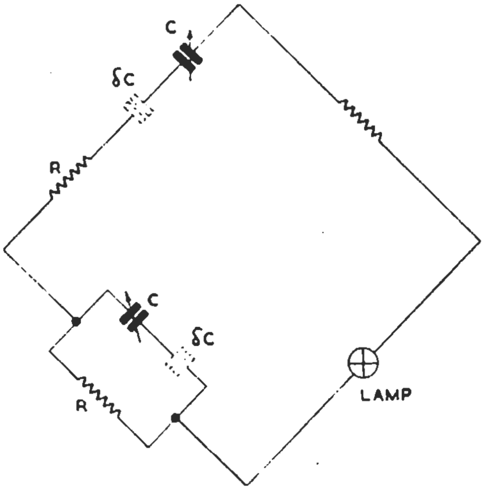

Fig. A.2. Wien Bridge with increment Capacitors

Production of Small Frequency-Changes

With any Wien-bridge controlled oscillator, small frequency changes of pre-determined value can conveniently be obtained by inserting or removing a subsidiary capacitance δC in series with each main tuning capitance C of the bridge circuit shown in Fig. A.2. These increments and decrements of frequency are of use in testing the response of narrow-band circuits.

Analysis

The oscillation frequency, f, under normal conditions is given by

$$f = \frac{1}{2\pi RC}$$

When δC is inserted, the resultant value of each capacitance in the bridge changes from C to

$$\frac{1}{1/C + 1/\delta C} = \frac{C \cdot \delta C}{C + \delta C}$$

The variation in capacitance alters the frequency from f to

$$f + \delta f = \frac{1}{2\pi R\left(\dfrac{C \cdot \delta C}{C + \delta C}\right)} = \frac{C + \delta C}{2\pi RC \cdot \delta C}$$

The resulting frequency change is equal to the difference between the new and the original frequency, and is given by

$$\delta f = \frac{C + \delta C}{2\pi RC \cdot \delta C} - \frac{1}{2\pi RC} \quad \text{i.e.,}$$

$$\delta f = \frac{1}{2\pi R \cdot \delta C} \quad \ldots \quad \ldots \quad \ldots \quad \text{(i)}$$

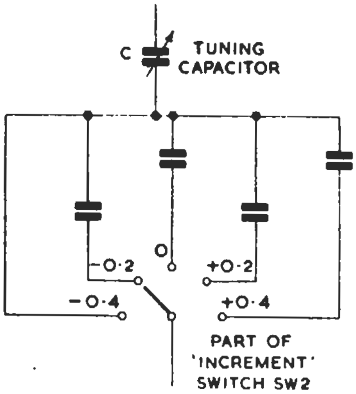

Fig. A.3. Frequency-increment Switching
Two similar circuits, one for each tuning capacitor

Practical Arrangement

A practical arrangement. applied to the PTS/12. is given in Fig 21 and is also shown in principle in Fig. A.3. This consists of a switch, SW2, by means of which any one of a group of capacitors can be inserted in each reactive arm of the bridge in series with the corresponding tuning capacitor.

It can be seen from equation (i) of the preceding subsection that, for a constant value of R, the frequency change introduced by a given capacitance δC is independent of the value of the tuning capacitor C. Thus, the frequency increments and decrements in any given range are fixed. When the range is changed, R is varied in the ratio of 10 : 1 or 100 : 1, and the frequency increments and decrements vary correspondingly.

The frequency *Increment* control of the PTS/12 has five settings, corresponding to frequency changes of —0·4, —0·2, 0, +0·2 and +0·4 c/s on ranges (1) and (2). The setting of —0·4 is obtained with no increment capacitor, and the remaining settings with increment capacitors of varying values.

The changes introduced on range (3) are 10 times, and on range (4) 100 times the above figures. G.H. 1253