

June 20, 1939.

L. A. MEACHAM
STABILIZED OSCILLATOR

2,163,403

Filed July 2, 1937

2 Sheets-Sheet 1

FIG. 1

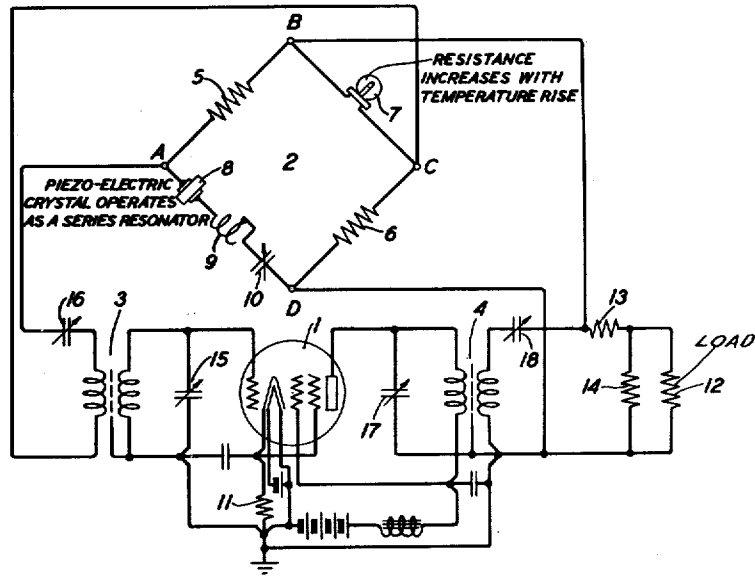


FIG. 2

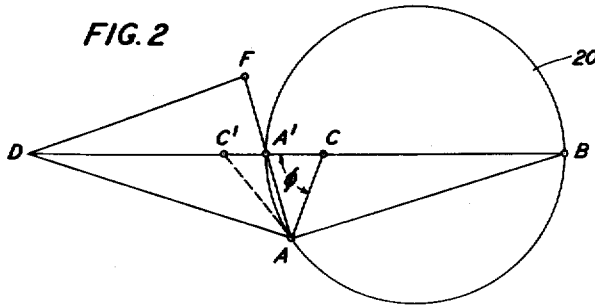


FIG. 3

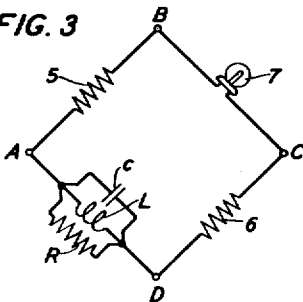
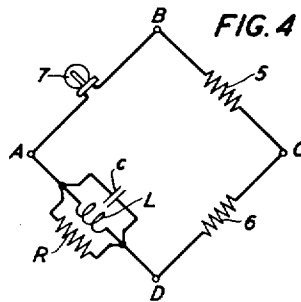


FIG. 4



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FIG. 5

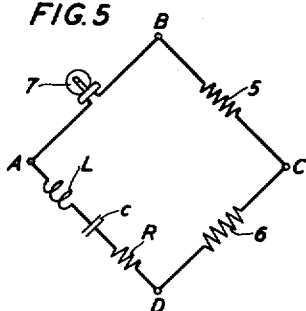


FIG. 6

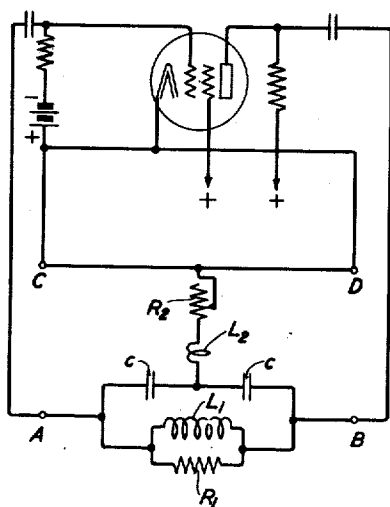


FIG. 7

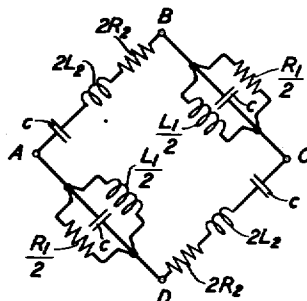


FIG. 8

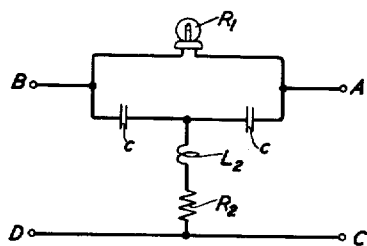
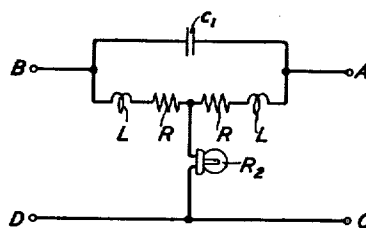


FIG. 9



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STABILIZED OSCILLATOR

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Application July 2, 1937, Serial No. 151,564

14 Claims. (Cl. 250—36)

This invention relates to vacuum tube oscillation generators of the feedback type and has for its principal object the improvement of the operating characteristics of such systems with respect to the stability of both the frequency and the amplitude of the generated oscillations. Another object is the improvement of the wave form of the oscillations and the suppression of harmonics of the fundamental frequency.

It has been shown by Llewellyn in an article entitled Constant Frequency Oscillators, Bell System Technical Journal, Vol. XI, No. 1, January 1932, that the frequency of the oscillations generated in a vacuum tube oscillator circuit is dependent, in the general case, on the resistances of the grid and plate space paths of the vacuum tube, and that one of the principal causes of frequency instability in the presence of variation of the tube excitation voltages is the non-linear character of these resistances. In oscillator circuits of the types now commonly used, these non-linear resistances are also productive of distortion of the oscillation wave form and the generation of harmonic frequencies.

In accordance with the invention improved frequency stability is achieved by the use of a special form of feedback circuit which makes the oscillation frequency substantially independent of the vacuum tube resistances and of variations of any impedance elements in the system other than a particular frequency determining combination. The amplitude of the oscillations is regulated and maintained substantially constant by automatic control of the magnitude of the feedback. The arrangements provided in accordance with the invention for the automatic control of the amplitude make it possible to operate the vacuum tube with its grid negatively biased to such an extent that no grid current is drawn, thereby eliminating the grid space path as a source of wave form distortion. These arrangements also permit the oscillations to be limited to a relatively small amplitude, within which the plate resistance of the tube is substantially linear and is not productive of distortion. The purity of the wave form is further enhanced by the characteristics of the feedback circuits of the invention which are such as to provide strong degenerative feedback at frequencies other than the oscillation frequency.

In one embodiment of the invention the feedback circuit comprises a Wheatstone's bridge one branch of which includes a frequency selective impedance, the other branches being constituted by resistances. At the oscillation frequency all four

branches are resistive thereby giving the feedback the necessary phase angle of 180 degrees independently of the tube resistances and, consequently, improving the frequency stability. At the oscillation frequency the magnitude of the feedback is determined by the degree of the resistance unbalance of the bridge. Preferably the circuit is operated with a very small amount of resistance unbalance and the frequency selective arm is made such that its reactance is strongly variable with frequency. As will be shown later this has the effect of rendering the frequency more stable in the presence of variations of the impedances in other parts of the circuit.

For the purpose of the automatic control of the feedback one of the resistive bridge arms is constituted by a variable resistance, the value of which, and therefore the degree of the bridge unbalance, is varied in response to variations of the strength of the current traversing it. Preferably this variable resistance is a linear element so that it does not cause any wave form distortion. It may, for example, consist of a lamp filament, metallic or carbon, in which case the resistance value is dependent on the operating temperature. By the inclusion of the variable resistance in the bridge circuit small changes in the strength of the current flowing in it produce large variations in the magnitude of the feedback thereby providing a close regulation of the oscillation amplitude.

In the accompanying drawings, Fig. 1 shows an embodiment of the invention;

Fig. 2 is a diagram useful in explaining the invention;

Figs. 3, 4 and 5 show modified forms of a portion of the system of Fig. 1;

Fig. 6 shows another embodiment of the invention;

Fig. 7 shows a network equivalent to a portion of the system of Fig. 6; and

Figs. 8 and 9 show other types of network that may be utilized in accordance with the invention.

The oscillation generator shown in Fig. 1 comprises a vacuum tube 1, preferably of the screen-grid, high amplification type, and a feedback path between the output and input circuits of the tube including an output transformer 4, a frequency selective Wheatstone bridge network 2, and an input transformer 3. Energizing circuits for the vacuum tube are provided as shown, the negative biasing potential for the control grid being obtained from a resistor 11 in the cathode lead which is traversed by the plate current. The grid bias is pref-

erably sufficiently large to prevent the flow of grid current in normal operation. A load impedance 12, which may be the input circuit of an amplifier, is connected to the secondary winding of output transformer 4 through a pad consisting of resistors 13 and 14.

It is desirable that the transformers 3 and 4 should introduce a very small phase shift and that the phase of the feedback should be controlled substantially exclusively by the selective bridge network 2. For low frequency systems the transformers may be of close coupled high efficiency type in which the phase shift is inherently small. In addition, or alternatively, the transformers may be tuned by condensers such as shown at 15, 16, 17, and 18, which may be adjusted to make the transformer phase shifts substantially zero at any desired frequency.

Two opposite arms of the bridge network comprise resistors 5 and 6, which are preferably equal. A third arm comprises a variable resistance device 7 such as the filament of a lamp, and the fourth arm includes a piezoelectric crystal 8, a small variable inductance 9 and a variable condenser 10. Frequency selective combination 8, 9, 10, exhibits a series resonance at a frequency somewhere near the series resonance of the crystal. Since the addition of a series inductance gives rise to a second resonance at a higher frequency, the value of inductance 9 should be very small so that the second resonance is far removed from that of the crystal. The transformers in the feedback path then operate to prevent possible oscillation at this frequency. Further, if the inductance is small any variations of its value will have correspondingly small effect on the oscillation frequency. Variable elements 9 and 10 are provided for the purpose of adjusting this oscillation frequency exactly to a desired value. In many cases one or other or both of these elements may be omitted. At its resonance frequency the impedance of the selective branch becomes purely resistive, its value being that of the resistance representing the dissipation in the circuit. Resistors 5 and 6 and device 7 should preferably have resistances of approximately this same value so that the bridge is only slightly unbalanced at the resonance frequency. The amount of the feedback is dependent on the degree of the bridge unbalance, but by using a high gain amplifier sufficient feedback to maintain oscillations can be obtained with a very small unbalance.

One pair of diagonally opposite corners, B and D, are connected to the output terminals of transformer 4 and the other pair, A and C, are connected to the terminals of input transformer 3. The requisite phase of the feedback for the production of oscillations may be obtained by poling the connections of one or other of the transformers or by interchanging the connections of the bridge corners.

The operation of the system is as follows: Assuming that the transformers produce no phase shift, the phase of the feedback becomes 180 degrees at the resonance frequency of the selective impedance 8, 9, 10, at which frequency the bridge circuit is purely resistive. Because of the purely resistive character of the bridge and of the absence of phase shift in the transformers, the feedback phase is independent of the non-linear resistances of the tube and oscillations occurring at this frequency are stable. Furthermore, under the assumed conditions, the phase of the

feedback can take the value of 180 degrees only at this resonance frequency.

Assuming the initial unbalance of the bridge to be such as to provide sufficient feedback, oscillations will start and will grow in amplitude until a condition of equilibrium is reached. Ordinarily this condition of equilibrium is reached only after the grid path of the vacuum tube becomes conductive and depends on the value of the grid path resistance. In the circuit of the invention, however, the steady oscillation amplitude is controlled and maintained by the automatic regulating action of the feedback network itself, the grid path of the tube remaining non-conductive. For this purpose the variable resistance device is so disposed in the circuit and has such characteristics that, as the oscillation amplitude increases, the bridge tends to become more nearly balanced, thereby diminishing the feedback. For example, if the device 7 consist of a metallic filament lamp, its resistance will have a positive temperature coefficient and will increase with increasing strength of the current traversing it. In this case the resistance of the lamp when cold should be less than that of the other bridge branches or less than is required to effect a balance of the bridge. The feedback at the moment of inception of the oscillations will be large, but, as the amplitude increases the temperature of the lamp filament will increase and also its resistance, thereby tending to bring the bridge into balance and to diminish the feedback. At some value of the current amplitude the lamp resistance would be such as to balance the bridge completely, thereby reducing the feedback to zero. Obviously the oscillation amplitude cannot reach this value but can only approach it asymptotically.

By the use of the bridge circuit arrangement, small changes in the lamp resistance have a multiplied effect on the amount of the feedback and a strong control is obtained which holds the oscillation amplitude constant with a high degree of accuracy. Adjustment of the operating amplitude to a desired value may be effected by changing the value of one or other of the fixed resistors 5 and 6. Adjustment of the oscillator output may be effected by variation of resistors 13 and 14.

In a particular circuit in which the bridge branches had resistances of about 100 ohms, a Western Electric Company, Incorporated No. 1A switchboard lamp was found to be suitable for use as the feedback control element.

Alternatively a variable resistor having a negative temperature coefficient, for example, a carbon filament lamp, may be used. In that case the cold resistance of the lamp should be greater than the resistance needed for balance of the bridge. The use of temperature controlled linear resistances, such as lamp filaments, has the advantage that control of the amplitude is effected without the production of wave form distortion. The control of the amplitude by means external to the tube also permits the tube to be operated without the overloading and consequent wave form distortion which ordinarily occur when the tube resistances control the amplitude.

Because of parasitic impedances or because of secular variation of the impedances external to the bridge, it may be found that the over-all feedback phase of 180 degrees is obtained at some frequency different from that of the resonance of the frequency selective bridge arm. Under this condition, the phase shift in the

bridge itself must be slightly different from 180 degrees at the oscillation frequency, the departure being just enough to compensate the phase shift in the other parts of the feedback path.

In accordance with the invention the effect of this upon the frequency stability is made negligibly small by the operation of the bridge in a nearly balanced condition and is further reduced by the use of elements in the frequency selective branch of the bridge having reactances that vary strongly with frequency at the resonance of the branch. A piezoelectric quartz crystal is well suited for this purpose.

The effect of the above-mentioned factors upon the frequency stability is illustrated by the vector diagram of Fig. 2. For the purpose of the explanation it will be assumed that the impedance of the path between the bridge corners A and C is sufficiently high so that the same current flows in the arms AB and AD and also in the arms BC and CD. In the diagram the vector DB represents the voltage impressed on the bridge between corners B and D from the output of the vacuum tube. Vectors DC and CB represent the voltages across the arms DC and CB, respectively, these being in phase with the impressed voltage since the branches are non-reactive. The voltage across the frequency selective arm DA is represented by the vector DA, this being the resultant of two quadrature components, namely, DF in phase with the current and representing the resistance drop, and FA representing the fall of potential in the reactance. The voltage across the branch AB is represented by the vector AB which is in phase with the resistance component DF.

It is readily shown that the locus of the end of the vector DA for variation of the reactance of the frequency selective branch is the circle 20, the center of which lies on the line of vector DB. The point A' at which the circle intersects the vector DB represents the potential of the bridge corner A at the resonance frequency. The voltage between the bridge corners A and C, that is, the output voltage of the bridge, is represented by the vector CA, its value at the resonance frequency being represented by CA'.

It is readily seen from the construction of the vector diagram that the phase angle ϕ between the input and output voltages of the bridge is dependent on the resistance unbalance of the bridge. When the degree of resistance unbalance is small the phase angle is very strongly variable with the reactance of the frequency selective branch at frequencies close to resonance. A relatively large phase shift produced by elements external to the bridge can therefore be compensated by the phase shift in the bridge itself resulting from an extremely small departure of the frequency from the resonance value. The operation of the bridge in a nearly balanced condition, therefore, increases the stability of the oscillation frequency.

Under the condition described above, that is, with the bridge proportions such that the point C in the vector diagram, Fig. 2, lies inside the circle 20, the variation of the reactance of the frequency selective branch between the values zero and infinity results in the movement of the end of the vector DA around the circle from the point A' to the point B and in the progressive variation of the angle ϕ through 180 degrees. A particular value of the phase shift can thus be produced by only one value of the reactance and at only one frequency. The compensation

of an external phase shift is therefore effected at a single frequency only and only one frequency of oscillation is possible.

On the other hand if the bridge is proportioned so that the point C lies outside the circle 20 as at C' a given value of the phase angle ϕ can result from two different reactance values, since the prolongation of the line C'A can also intersect the circle 20 at another point corresponding to a different reactance. Compensation of an external phase shift thus becomes possible at two different frequencies and oscillations may occur at either.

To prevent the occurrence of two possible frequencies of oscillation it is therefore necessary to impose certain restrictions on the proportions of the resistances of the bridge arms and this in turn determines the character of the variable resistance to be used for the feedback control. In the circuit as shown in Fig. 1, the requirement ensuring a single oscillation frequency is met by making the resistance of the lamp Γ less than enough to balance the bridge. To effect the control of the feedback the lamp filament must then have a positive temperature coefficient. In general, the resistances of the bridge arms should be so related that a complete phase reversal of the output voltage occurs as the reactance of the reactance elements changes from zero to an infinite value. The necessary resistance relationship can be determined readily by means of this criterion in any particular case.

The vector diagram of Fig. 2 shows also that, as the frequency departs from the resonance frequency of the selective bridge arm, the total unbalance of the bridge and, therefore, the amount of the feedback, increases very rapidly and acquires such phase as to produce a strong degenerative action. At harmonic frequencies of the fundamental oscillation the system operates as a degenerative feedback amplifier and any harmonics that may be generated are subject to strong attenuation.

In the circuit shown in Fig. 1 the oscillation frequency is that of the series resonance of the selective bridge arm. The piezoelectric crystal which constitutes the selective impedance has also an anti-resonance at an adjacent frequency, but at this frequency the phase of the output voltage of the bridge is opposite to that required for oscillation. In modified forms of the invention the oscillation frequency may be determined by the anti-resonance of a selective impedance, examples of bridge circuits of this type being shown in Figs. 3 and 4.

The frequency selective arm in the circuit of Fig. 3 comprises the parallel combination of a capacity C, an inductance L and a resistance R. The resistance may represent the energy dissipation in the inductance or it may include an actual resistance element. At the frequency of the parallel resonance of L and C, the impedance of the anti-resonant circuit becomes purely resistive, with the resistance large as compared with R so that the impedance of the arm as a whole is a resistance which is substantially equal to R. The variable resistance element Γ is included in the branch BC as in Fig. 1. For this circuit configuration the prevention of oscillation at an undesired frequency requires the variable element Γ to have a resistance greater than that needed to balance the bridge. For amplitude control purposes its temperature coefficient must therefore be negative. In Fig. 4 the variable element is included in a branch adjacent the

selective impedance. Its value in this position should be less than that required for bridge balance and its temperature coefficient should be positive.

Fig. 5 shows a bridge circuit of similar type to that of Fig. 1 in which the crystal resonator is replaced by a simple series resonant circuit including resistance. The feedback control element is inserted in a branch adjacent the selective impedance. The variable element should have, in this position, a resistance greater than needed for bridge balance and should have a negative temperature coefficient. With either type of selective impedance, the variable element may be included in the same arm as the selective impedance if desired. In that case, if the selective impedance is of the series resonant type, the variable element should have a positive temperature coefficient and should have a negative coefficient if the impedance is parallel resonant.

A further modification of the invention is shown in Fig. 6 in which the feedback network is constituted by a frequency selective bridged-T network. The unbalanced configuration of this network permits it to be inserted in the oscillator circuit as shown without the use of coupling transformers although these may be included if desired. The network comprises a pair of series branches constituted by equal capacities of value C, a shunt branch including an inductance L_2 and a resistance R_2 , and a bridging branch comprising an inductance L_1 and a resistance R_1 in parallel. The inductance and resistance elements are proportioned so that L_1 is equal to $4L_2$ and R_1 is slightly greater than $4R_2$. The oscillation frequency is determined by the resonance of L_1 with the two capacities in series. Resistances R_1 and R_2 are preferably actual resistors, their values being proportioned with proper allowance for the effective resistances of the inductances. Either resistor may be made automatically variable in response to current changes to provide the feedback control in accordance with the invention. If the bridging resistance R_1 be used for this purpose its temperature coefficient must be negative and if the shunt resistance R_2 be used, its temperature coefficient must be positive. In the figure, the shunt resistance R_2 is indicated as the variable feedback control element.

The bridged-T network shown in Fig. 6 is equivalent, with respect to its transmission characteristics to the symmetrical Wheatstone's bridge shown in Fig. 7. The input and output terminals of the two networks are correspondingly designated and the element values in Fig. 7 are indicated in relation to the corresponding elements in Fig. 6. From the relationship imposed on inductances L_1 and L_2 in Fig. 6, it follows that branches AB and CD of the equivalent bridge are resonant at the same frequency at which the branches AD and BC become anti-resonant. At this frequency the bridge arms all become purely resistive and the output voltage is dependent only upon the amount of the resistance unbalance. The output voltage will be either in phase with or in opposition to the impressed voltage according to the sense of the resistance unbalance and, since the bridge arms are purely resistive, the phase relationship of the voltages is independent of the connected terminal impedances. When used as an oscillator feedback network the bridge circuit of Fig. 7 provides stability of the oscillation frequency. The equivalent bridged-T circuit of Fig. 6, there-

fore, likewise provides frequency stability. The possibility of oscillation at an undesired frequency, when a phase shift is introduced by other elements in the feedback path, is prevented by making the resistance R_1 somewhat greater than $4R_2$.

The circuits described above are all characterized by the property that their image impedances are purely resistive at the frequency for which the phase shift components of their image transfer constants take the value π or 180 degrees. Because of this relationship, the over-all insertion phase shifts, when the networks are inserted between resistive source and load impedances, take the value of 180 degrees at frequencies determined solely by the image transfer constant characteristics and independently of the magnitudes of the terminal resistances. When such networks are used as feedback networks in vacuum tube oscillator circuits, the requisite phase shift for the production of oscillations is obtained at a frequency which is independent of the space path resistances of the vacuum tube and is therefore stable.

The automatic control of the oscillation amplitude, which is a feature of the invention, may be applied also to circuits which do not conform exactly to the above-mentioned relationship. Feedback networks of this type are illustrated in Figs. 8 and 9. The network shown in Fig. 8 is a bridged-T network similar to that of Fig. 6, but having the bridging inductance L_1 omitted. The bridging resistance R_1 constitutes the variable feedback control element. As in the case of Fig. 6, R_1 should be somewhat greater than $4R_2$ and for control purposes should have a negative temperature coefficient. The oscillation frequency lies very close to the value determined by the product $2L_2C$. Stability of the oscillation frequency is obtained by making the difference between R_1 and $4R_2$ very small, that is, by making the attenuation in the network very great at the oscillation frequency, and is enhanced by making the capacity C small and the inductance L_2 large.

In the circuit of Fig. 9, the bridging impedance is a capacity C_1 , the T-network comprises equal series branches of inductance L and resistance R, and the shunt branch consists of a variable resistance R_2 which constitutes the feedback control. The operating conditions are readily found from inspection of the equivalent Wheatstone's bridge, or lattice, obtained by well-known methods. The oscillation frequency is approximately that determined by the product $2LC_1$. The resistance R_2 should be slightly less than the value

$$\frac{L}{2C_1R} - \frac{R}{2}$$

and for control purposes should have a positive temperature coefficient. For enhancement of the frequency stability the inductance L should be small and the capacity C_1 large.

While the invention has been described in connection with particular embodiments, certain variations have been suggested, and it is to be understood that many additional changes are possible within the scope of the invention. For example, other forms of balanced circuits may be used instead of a Wheatstone bridge or a bridged-T network and additional stages of amplification may be employed.

What is claimed is:

1. An oscillation generator comprising an amplifier, input and output circuits therefor, and a Wheatstone bridge network coupling said input

and output circuits, the bridge arms including a resonator and a resistance, the latter being variable with temperature.

2. An oscillator comprising an amplifier and a feedback circuit therefor, the latter including a bridge network containing a series resonant element in one arm and a thermally variable resistor in the opposite arm, said resistor having a positive temperature coefficient of resistance variation.

3. An oscillation generating system comprising an amplifier, input and output circuits therefor, and a Wheatstone bridge network connecting said input and output circuits, one arm of the bridge containing a resonant element and another arm containing a lamp the resistance of which is a function of its temperature.

4. An oscillator comprising an amplifier and a feedback circuit therefor, the latter including a Wheatstone bridge containing a series resonant element in one bridge arm and a resistor having a negative temperature coefficient of resistance change in an adjacent bridge arm.

5. An oscillator comprising an amplifier and a feedback circuit therefor, the latter including a Wheatstone bridge network having a parallel resonant tuning element in one bridge arm and a resistance with a negative temperature coefficient in the opposite bridge arm.

6. An oscillation generator comprising an amplifier having an input circuit and an output circuit, and a bridge network having two opposite arms comprising fixed resistances and having a resistor whose resistance varies as in accordance with its current and a tuned circuit respectively in the remaining arms, the input and output circuits of the amplifier being connected across the respective diagonals of the bridge, whereby both the amplitude and the frequency of oscillations are stabilized.

7. In an oscillation generator, a feedback circuit including a Wheatstone bridge with a series resonant tuning element in one bridge arm and a resistance with a positive temperature coefficient of resistance change in the opposite bridge arm.

8. In an oscillation generator, a feedback circuit including a bridge having a series resonant element in one bridge arm and a negative temperature coefficient resistor in an adjacent bridge arm.

9. In an oscillation generator, a feedback bridge circuit with a parallel resonant tuned circuit in one bridge arm and a resistance with a negative temperature coefficient of resistance change in the opposite bridge arm.

10. In an oscillation generator comprising an amplifier and a feedback path coupling the output and the input terminals of the amplifier, a frequency determining network included in said feedback path, said network having a frequency selective transmission characteristic providing a minimum feedback in regenerative phase substantially at the oscillation frequency and strong degenerative feedback at frequencies removed therefrom, and means forming part of said network for controlling the amount of the said minimum feedback in response to variations of the oscillation amplitude whereby the oscillation amplitude is maintained substantially constant, said means comprising a circuit element having an impedance variable in magnitude with the strength of the current traversing it.

11. In an oscillation generator comprising an amplifier and a feedback path coupling the output and the input terminals of the amplifier, a frequency determining network included in said feedback path, said network having a frequency selective transmission characteristic providing a minimum feedback in regenerative phase substantially at the oscillation frequency and strong degenerative feedback at frequencies removed therefrom, and means forming part of said network for selectively controlling the amount of the said minimum feedback in response to variations of the oscillation amplitude whereby the oscillation amplitude is maintained substantially constant, said means comprising a circuit element having an impedance variable in magnitude with the strength of the current traversing it.

12. In an oscillation generator comprising an amplifier and a feedback path coupling the output and the input terminals of the amplifier, a frequency determining network included in said feedback path, said network having a frequency selective transmission characteristic providing a minimum feedback in regenerative phase substantially at the oscillation frequency and strong degenerative feedback at frequencies removed therefrom, and a resistance element included in said network the resistance of which, in relation to other resistances in said network, determines the amount of the said minimum feedback and is variable with the current strength therein in such sense as to diminish the feedback in response to an increase in the oscillation amplitude, whereby the oscillation amplitude is maintained substantially constant.

13. An oscillation generator comprising an amplifier, a feedback path coupling the output and the input terminals of the amplifier, and a frequency determining network included in said feedback path, said network having a maximum attenuation substantially at the oscillation frequency and relatively low attenuation at other frequencies, and a resistance element included in said network the resistance of which determines the amount of the attenuation of said network at the oscillation frequency and is variable in response to variations of the oscillation amplitude in such sense as to maintain the amplitude substantially constant.

14. An oscillation generator comprising an amplifier, a feedback path coupling the output and the input terminals of the amplifier, and a frequency determining network included in said feedback path comprising a Wheatstone bridge circuit proportioned to have a small unbalance productive of regenerative feedback at the oscillation frequency, a resonant impedance included in an arm of said bridge circuit, the resonance of said impedance substantially determining the oscillation frequency, and an impedance element the impedance of which is variable in response to variations of the oscillation amplitude included in another arm of said bridge circuit, said variable impedance operating to diminish the unbalance of the bridge circuit as the oscillation amplitude increases, whereby substantial constancy of amplitude is maintained.

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