March 10, 1942. L. A. MEACHAM 2,275,452

STABILIZED VACUUM TUBE OSCILLATOR

Filed June 24, 1939 2 Sheets-Sheet 1

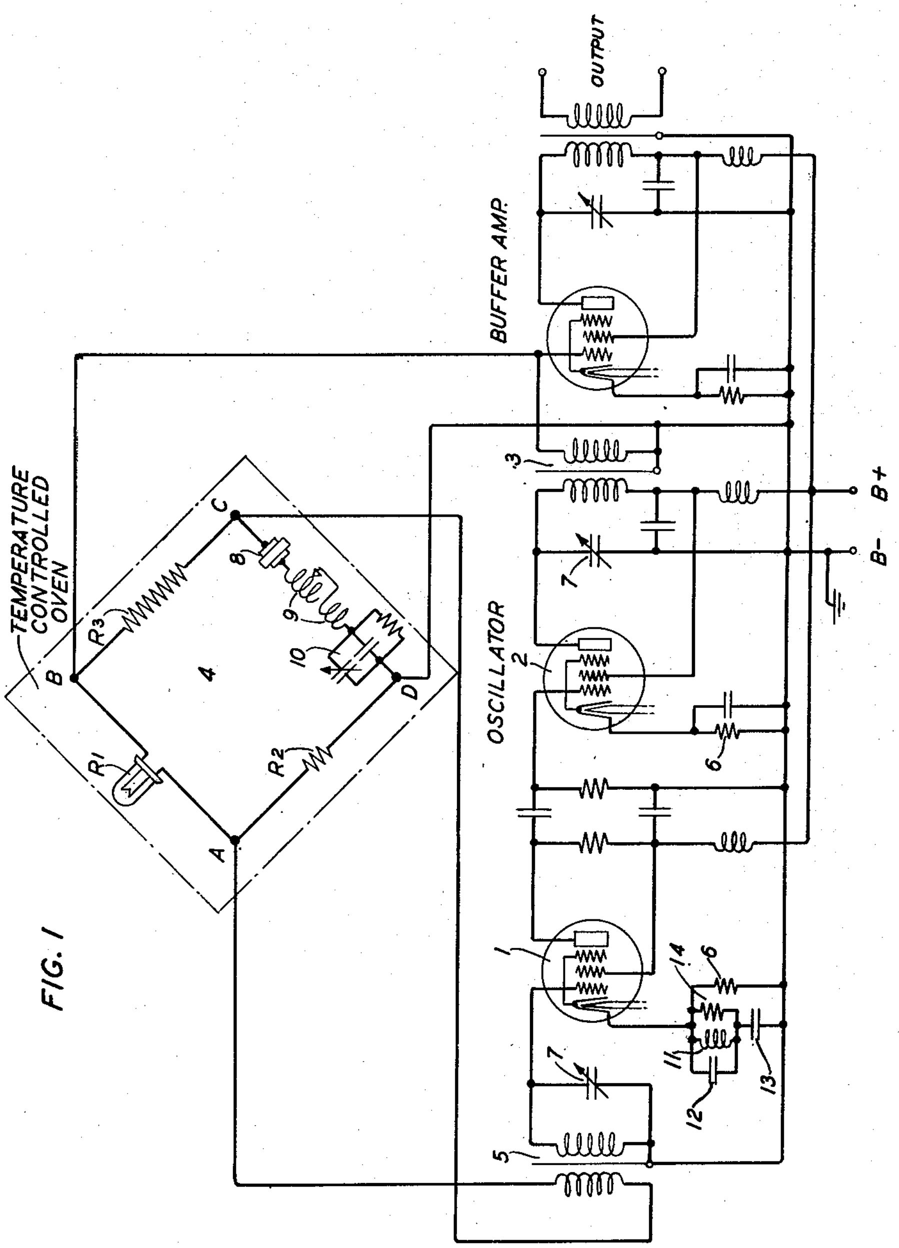

FIG. 1

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Filed June 24, 1939 2 Sheets-Sheet 2

FIG. 2

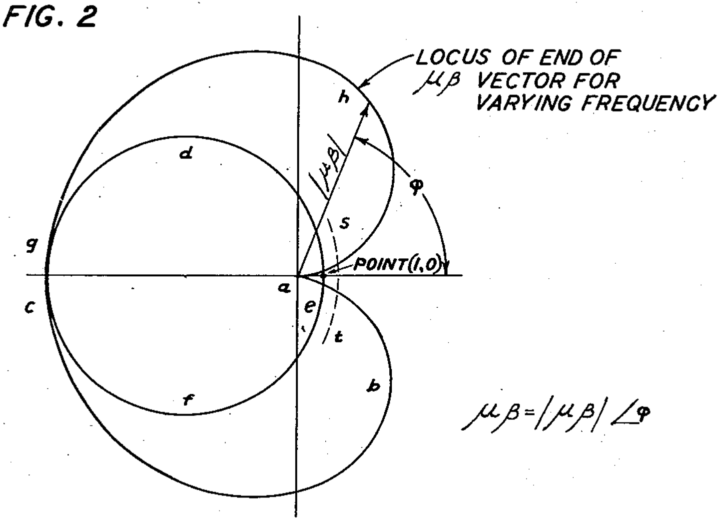
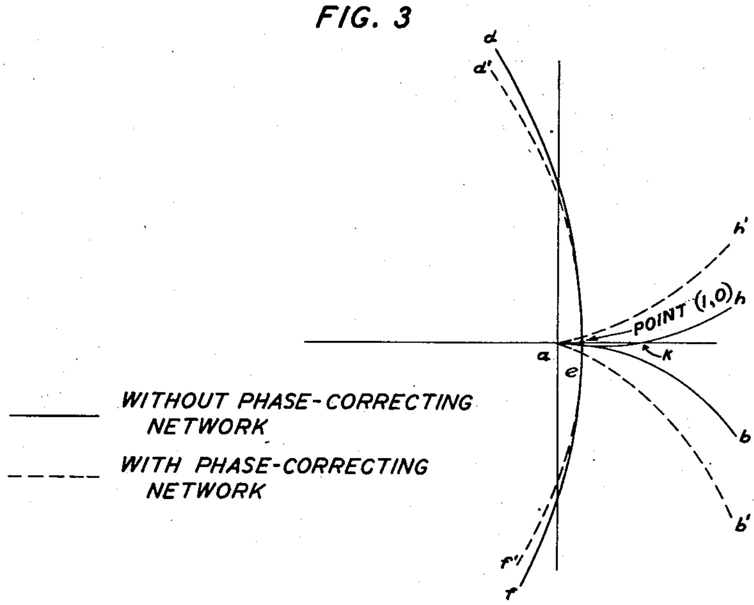


FIG. 3



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STABILIZED VACUUM TUBE OSCILLATOR

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12 Claims. (Cl. 250—36)

This invention relates to vacuum tube oscillation generators of the feedback type and, specifically, represents an improved and more highly elaborated form of the prototype circuit as disclosed in applicant's Patent 2,163,403, having issue date of June 20, 1939.

It is the principal object of the invention to still further improve the operating characteristics of such circuit with respect both to frequency stability and amplitude stability of the generated oscillations. A subsidiary object is the further improvement of the wave form of the resultant oscillations. Experiment has shown that the generic circuit, as matured into the form represented by the present invention, has a frequency stability many times as great as that of the circuit of the above-identified patent.

The prototype circuit evinced a recognition of the fact that the frequency of oscillations generated in vacuum tube oscillator circuits is dependent, in the general case, on the resistances of the grid and plate space paths of the 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, these non-linear resistances being also productive of distortion of the wave form and the generation of harmonic frequencies. A remedy was found in 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 element 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, which makes 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. Because of the limitation to a relatively small amplitude of current traversing the feedback path, the plate resistance of the tube is made substantially linear and therefore non-productive of distortion. Also the purity of the wave form is enhanced by the characteristic of the feedback circuit, which is such as to provide strong degenerative feedback at frequencies other than the oscillation frequency.

The feedback circuit, and therefore the elements principally distinguishing the invention of the prototype circuit as being responsible for the very great improvement along the lines indicated, is characterized by 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 including in itself means for controlling the amount of said minimum feedback in response to variations of the amplitude oscillation so that said amplitude is maintained substantially constant.

In one embodiment of the said prototype invention, this corresponding also to the single embodiment to be disclosed in the present specification, the feedback circuit comprises a Wheatstone bridge having its diagonals conjugately connected to the input and output circuits of the vacuum tube amplifier. One branch includes a frequency selective impedance, such as a piezoelectric crystal or a like mechanical vibratory element or the electrical analogue thereof, the other branches being constituted by resistances. At the oscillation frequency all four branches are resistive because control is effected at the frequency where said impedance operates at or near series resonance. Since with perfect balance there would be no feedback, the circuit is operated with a very small amount of resistance unbalance. Because of the operation of the bridge principle, when the bridge is in a nearly balanced condition, any phase shifts in the oscillator outside of the feedback network itself, and which would tend to cause the over-all feed-back phase shift of zero degrees, necessary for oscillation, to occur at some frequency slightly different from that of the resonance of the frequency selective bridge arm, would be compensated in a greatly magnified degree by the resultant change in condition of the network. This is illustrated well by the vector diagram constituting Fig. 2 of the above patent disclosing the prototype circuit. Thereby the effect of phase shift upon frequency stability is made negligibly small. Frequency stability is further enhanced by the use of an element in the frequency selective branch having a reactance that varies strongly with frequency about the resonance frequency of the branch. For that reason a piezoelectric crystal is found well suited for the purpose. By reason of the amplitude limiting means being included in the bridge network, small changes in its resistance by which control is effected, have a multiplied effect on the feedback, similarly as in the above instance of frequency control, so that a correspondingly stronger control is obtained tending to hold the oscillation amplitude constant, with its attendant benefits by way of constancy of frequency and of wave form as well as of purity of wave form.

The circuit of the present invention differs from the prototype circuit, as to continuity and electrical dimensions in three particulars, namely:

(1) The network is so relatively electrically dimensioned that the mechanical vibrating element, piezoelectric crystal in the instance to be disclosed, vibrates at a much lower amplitude than has been used in previous circuits of this type, which means that a much smaller potential is impressed thereacross, the same being true if or when the electrical equivalent circuit is used in place of the mechanical vibrating element. Low amplitude operation is especially desirable with certain types of resonators such as the piezoelectric crystal for a number of reasons, including reduction in wear on the resonators and their mountings, reduction of heat dissipation therein, improved rigidity and permanency of mounting, and other improvements in the observed characteristics of these devices which affect their short-time and long-time stabilities. To secure the above reduction of amplitude and at the same time to continue to supply an adequate amount of power to the thermally adjusted balance-controlling means (any known type of which is found to be insensitive to amplitude changes if the power dissipated therein is extremely small), the network (bridge) has been given radically unequal arms or branches. The inequality is such, in a practical instance, that the current through the lamp exceeds that through the crystal by a factor of about 16.

(2) As a bridge of unequal arms is less efficient than one having four equal resistances, it is found that more amplification is necessary in the oscillator, modified as in (1) above, if the same high sensitivity of balance, and accordingly the same degree of frequency and amplitude stabilization, is to be secured as in the prototype oscillator. In the above instant case, an increase of about 20 decibels is required in the gain of the vacuum-tube amplifier, and in fact still more gain is desirable to further improve the balance sensitivity and the stability; hence, a second stage of amplification is provided.

(3) With large amounts of amplification, employed either for the reasons specified above or for any other reason, there is an inducement toward singing at unwanted frequencies, as will be brought out in the detailed description of the invention. Hence, an additional negative feedback is provided, entirely independently of any degenerative action of the bridge itself, to annul this tendency to sing. This is accomplished by a cathode network common to the input and output circuits of one of the amplifier tubes (or by a plurality of such circuits so disposed in relation to their respective tubes), containing, besides a resistor which determines the maximum impedance of the network, an anti-resonant circuit, tuned to the wanted frequency which is 100 kilocycles in the practical instance recited. At this wanted frequency, the network is resistive, and introduces a small amount of degenerative feedback which reduces the gain of the amplifier slightly without affecting its phase. At other frequencies, however, the impedance of the cathode network is either capacitive (for higher frequencies) or inductive (for lower frequencies); hence the degenerative feedback takes on a frequency-variable phase angle and introduces corresponding phase shifts in the transmission through the amplifier. These phase shifts are in general of such a nature as to partially counteract the phase shifts produced by the various other reactances of the vacuum-tube amplifier, and in particular may be chosen to avoid approaching the conditions for oscillation at the frequency or frequencies where undesired singing would otherwise tend to occur. Thus at the expense of a small decrease in amplification at the wanted oscillation frequency, desirable protective phase shifts are achieved at other frequencies.

In the accompanying drawings:

Fig. 1 illustrates an embodiment of the invention; and

Figs. 2 and 3 are so-called $\mu\beta$ diagrams in polar coordinates showing respectively certain attributes of the circuit of Fig. 1 without and with the additional features characterizing this circuit as compared with the prototype circuit.

The oscillation generator as a whole, as disclosed in Fig. 1, comprises an oscillator proper and a buffer amplifier, the latter, as its name implies, being adapted to function to prevent reaction from the load or "output," indicated in the figure as connected to the output electrodes of said buffer amplifier, to the oscillator proper. This buffer amplifier is not an essential element of the invention and, on occasion, may be dispensed with. These two elements are indicated by name in Fig. 1.

The oscillator (that is, what has been before designated as the "oscillator proper") comprises a multistage vacuum tube amplifier constituted principally by vacuum tubes 1 and 2 and a feedback path between the output and input circuits of the amplifier and, therefore, including in order of energy transfer, the output transformer 3, a frequency selective network 4 having the characteristic pointed out in the statement of invention and here illustrated as a Wheatstone bridge, and an input transformer 5.

The choice of amplifier tube is not critical although perhaps the tube should preferably be of the screen-grid high amplification type as shown. Likewise, the type of coupling therebetween is not critical except that it should introduce but little phase shift over the pass-band of the transformers 3 and 5. The drawing illustrates a conventional type of condenser-resistance coupling. In the particular oscillator contemplated throughout the specification as having been found very effective by experiment, the second stage of amplification was provided principally to make up for a 20 decibel loss, as compared with the prototype circuit, because of the bridge dissymmetry, this being an important feature of the invention. The power gain from the input to the low winding of the transformer corresponding to transformer 5 of Fig. 1 to the output from the low winding of the transformer corresponding to transformer 3, terminated in matching impedances, was 70 decibels.

Energizing circuits for the anodes of the tubes are provided as shown. The heater circuits for the tube cathodes are shown in incomplete form. These heaters may be energized, interconnected, and connected to their associated circuits, all as in accordance with conventional practice between which there is a choice of alternatives. Negative biasing potentials for the control grids are obtained from resistors 6 in the cathode leads, which are traversed by the plate current and from which alternating components thereof are effectually excluded in the case of the second tube by the shunting capacitance shown. Preferably the grid bias potentials are sufficiently large to prevent the flow of grid current in normal operation. The cathode network, exclusive of resistor **6**, for the first tube, is for the purpose of providing a critical negative feedback as in accordance with principles which will be discussed in another place. It might just as well affect the second tube or both tubes instead of only the first tube as shown. It is desirable that the transformers **3** and **5** should introduce as small phase shifts as possible so that the bridge may operate substantially at exact reactive balance. To that end the transformers may be tuned by use of capacitors **7** which may be adjusted so that the transformer phase shifts are substantially zero at the desired frequency.

Consistent with its sole function of preventing reaction from the load circuit connected to its output to the anterior oscillator proper, the buffer amplifier shown at the right may be of a choice of conventional types. For convenience and as shown, it may be of the same general type as the unit amplifiers of the oscillator proper. As is evident from the drawings, it obtains its plate energization and grid bias in a similar manner, and it may be coupled to the load, in a similar manner, through a tuned circuit as shown.

The feedback network **4** is, in the specific form disclosed, a true Wheatstone bridge. Specifically the bridge, at the operating point of the crystal **8**, which controls the frequency, is comprised wholly of pure resistances except to the extent that the reactance branch or arm consisting of the crystal **8** and series impedance elements **9** and **10** might deviate slightly from the optimum series resonance condition, as might result, for example, by phase changes in the amplifier or in the transformers, in fact anywhere exteriorly of the bridge network itself. Under ideal conditions with zero phase shift in the transformers and in the coupling between the tubes so that the round trip path exteriorly of the bridge is effectively reactanceless, the reactance arm would operate at series resonance so as to effectively constitute a pure resistance. The principles of operation, as to this feature, are the same as in the circuit of applicant's patent above identified and the description therein, especially with reference to the vector diagram of Fig. 2 therein, is believed to be adequate.

Two opposite arms of the bridge network comprise resistors R_2 and R_3. A third arm comprises a variable resistance device R_1 such as the filament of a lamp, that is a resistance which has a pronounced positive temperature coefficient. The fourth arm, as above explained, comprises a crystal **8** and impedance elements **9** and **10**. One pair of diagonally opposite corners A and C are connected to the terminals of input transformer **5**, the other corners B and D being connected correspondingly to the terminals of output transformer **3**. The requisite phase of the feedback production of oscillation, other things being equal, may be obtained by poling the connections of one or other of the transformers or by interchanging the connections of the bridge corners. Since the operating point of the crystal will tend automatically to vary from series resonance conditions to compensate for extraneous phase shifts, as indicated by Fig. 2 of applicant's patent, above mentioned, the use of series impedances **9** and **10**, each of which is variable as indicated, is not necessary in all instances. However, these impedance elements are capable of the conventional function of a so-called trimming impedance to effectively slightly change the control frequency otherwise determined solely by the crystal. In the performance of this function a single type of reactance instead of the combination of the two types in series, could be used although with somewhat less flexibility, or said trimming impedance portion of the bridge network could be connected in shunt instead of in series with the crystal whether one or both types of reactance are used.

The operation of the bridge principle, as is evident from the disclosure in the applicant's previous patent, supra, is most effective when the bridge is most nearly balanced because with this condition the maximum variation of magnitude and phase of the fed back potential occurs with a given change of impedance of a bridge arm. Such change in bridge arm impedance might result for example by the control action of the crystal when changing from its optimum condition of series resonance, corresponding to zero reactance, to a finite reactance, responsive to a change in outside conditions. The amount of the feedback is, of course, 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.

These various considerations, in the instance of the previous bridge oscillator, had dictated the use of a fairly symmetrical bridge, that is, a bridge with nearly equal arms, the said previous oscillator differing radically from the present considered oscillator in that particular. The necessity of using for arm R_1 a resistance variable with temperature, within practical limitations of choice, imposes certain requirements on the bridge, affecting the matter of symmetry. In the case of the previous oscillator, the necessary conditions were easily satisfied. That is, with the use of an effective type of element for R_1, the bridge could be balanced with a desirable degree of symmetry and with a resultant efficient potential on the crystal for effective drive, it being found further that an ample degree of amplification using a single tube was possible, having in mind the maximum stability then perceived to be required. The situation differs, in the instant case, because of the appreciation of the very great benefit accruing from driving the crystal at an amplitude very much less than was used before.

In order to bring about this low amplitude of crystal vibration, hence low amplitude of potential impressed across the crystal bridge arm, with approximately the same value of thermally responsive resistance of resistor R_1 and of course assuming a condition of near balance, it is necessary to make the resistance of R_2 very small as compared with the resistance of R_3. In the practical instance cited several times in this specification, a typical value of R_2 was 2.8 ohms and that of R_3 was 2,000 ohms. It will be recalled that in the previous bridge stabilized oscillator these resistances had substantially the same value. The ultimate result is that with such radically unlike arms more gain is necessary to secure the same sensitivity of balance. This condition provides the necessity for the second stage of amplification. Actually in the circuit tested, the bridge dissymmetry resulted in an effective reduction of 20 decibels in the gain of the amplifier circuit. The second stage of amplification not only made up this loss but provided a certain additional gain, the power gain from the input to the low winding of the input transformer to the output of the low winding of the output transformer being 70 decibels.

Analysis of the purpose and function of the cathode network, consisting of elements 6, 11, 12, 13 and 14, by which a special negative feedback about tube 1 is induced, will be facilitated by preceding it with a discussion of Figs. 2 and 3. Figs. 2 and 3 are diagrams illustrating, in a simple way, the characteristics of operation of the system. The curves are plotted in polar coordinates between the scalar values of the product $\mu\beta$ and the angle Φ, the $\mu\beta$ product being a measure of the total gain in the round trip path and the angle Φ the corresponding phase change in the round trip path. This type of diagram is old in the art under the common denomination "$\mu\beta$ diagram." Examples are given in the paper by H. S. Black "Stabilized Feedback Amplifiers" in the January, 1934, issue of the Bell System Technical Journal. In a general way the information derivable from these Figs. 2 and 3 diagrams is comparable as to kind and extent with that derivable from the vector diagram of Fig. 2 of the previous patent although the latter described merely the operation of the bridge, whereas the $\mu\beta$ diagrams deal with the entire circuit.

Fig. 2 shows the "$\mu\beta$ characteristic" of a bridge stabilized oscillator having a relatively small amount of gain and therefore requiring no phase-correcting cathode network. It therefore implies a circuit like that of the previous patent. It discloses the general form of the locus and is useful as teaching that for increasing frequency the values of $\mu\beta$ follow the particular sequence illustrated. That is, for increasing frequency, the end of the $\mu\beta$ vector follows the path *abcdefgha*, covering the portion *abc* as the frequency changes from zero to very nearly that of the crystal (a function of the properties of the output and input transformers), the portion *cdefg* in an exceedingly narrow frequency band (determined largely by the bridge and corresponding as to frequency range with the circle locus 20 of Fig. 2 of the previous patent) and the portion *gha* in the range from slightly above the crystal resonance to infinity (again a function of the transformers). According to theory well known in the art, oscillation commences if the loop encloses the point having the coordinate 1, 0 as indicated on the figure. When the amplitude is small and the lamp R_1 is cool, the bridge is so unbalanced that the loop does enclose this point as indicated by the broken locus *st*. As the amplitude increases the lamp filament becomes warmer, moving the locus *st* to the left until it passes exactly through said point 1, 0. The frequency represented by the point on this curve which then coincides with 1, 0 is the frequency of oscillation. In the Fig. 2 diagram, the portion *def* of the locus is the only portion which can enclose this point; hence there is no danger of an undesired oscillation at some other frequency than the one above mentioned, this portion *def* being a part of the inner loop responsive to control by the crystal and the thermally-adjusted resistor R_1.

The Fig. 3 diagram is similar to that of Fig. 2, the difference being that it assumes conditions corresponding to that of the present invention, that is, with the value of μ greatly increased by the use of an additional stage or stages of amplification. It results that with the diagram drawn to the same scale as Fig. 2, much of the locus is outside the boundary of the drawing. As before, and now referring to the solid curve, the lamp should adjust the portion of the curve *def* to pass through the point 1, 0 exactly without complication as by the incidence of conditions tending to cause the curve as a whole to have another crossing point, for instance, at 1, 0 or on the zero axis outside that point. However, with the circuit differing from that contemplated by Fig. 2 only by the use of an increased μ this is impossible because with the curve magnified by increased gain, the point *k* at which it crosses the zero axis is on the right-hand side of point 1, 0, so that the curve as a whole encloses the 1, 0 point twice. In such an instance, the circuit is found to oscillate at a high frequency represented by point *k* which, however, is actually moved leftward to coincide with said point 1, 0 by the ultimate decrease in μ resulting from tube overloading, since there can be no stable oscillations except at this point 1, 0. Oscillation at a point on the portion *def* may also occur, but with reduced stability because of loss of gain, the presence of harmonics and the heating effect of the unwanted high frequency current, which may vary from time to time in frequency and amplitude, in the balance-controlling lamp.

At the low-frequency end *ab* of the $\mu\beta$ locus, the point 1, 0 is not quite enclosed but there is very little phase margin; hence, some minor change in the circuit might lead to enclosure, accompanied by further undesired oscillations. It should be realized that the form of the curve in Fig. 3 may be varied considerably by the design of the transformers and other circuit elements, and that either or both of the portions *ab* and *ha* may intersect the axis of zero phase to the right of point 1, 0, at points such as *k*. Fig. 3 merely illustrates one form of the curve, which happens to apply to the particular experimental embodiment referred to previously.

The cathode network is designed to introduce phase shifts at both the high and low frequency ends of the locus, which move the critical parts back away from the point 1, 0 as shown by the broken curve in this Fig. 3, thus protecting against extraneous frequency singing. While this is done at the expense of a small decrease in gain (about 3 decibels in the particular circuit tested) which effectively reduces the diameter of the inner loop *def*, the additional amplification which the protection against singing makes possible is substantially greater than this loss; thus an improvement in net gain and in frequency stability may be utilized.

The functions of the various elements of this cathode network are as follows: The resistant 6, traversed in particular by the direct current component of the plate current of tube 1, provides bias between the grid and cathode of this tube. The inductance 11 and the capacitance 12 are anti-resonant at the wanted frequency of the oscillator, and have the function of providing reactances of suitable magnitudes in the cathode path at other frequencies, in order to afford, by means of local feed-back about tube 1, desirable phase shifts in the transmission about the oscillator loop. The capacitance 13 is large, so that it acts as a by-pass; it is employed to prevent the direct current component of the plate current from being short-circuited by the inductance 11. The resistance 14, in parallel with resistance 6, determines the magnitude of the negative feed-back at the operating or wanted frequency.

Now at this wanted frequency, for which the reactive elements 11 and 12 are anti-resonant, the local feedback is resistive in nature and does not introduce any phase shift. Furthermore, at very much higher frequencies, the reactance of capacitance 12 is small and the impedance in the cathode circuit is very low; hence there is little local feedback, and practically no phase shift is introduced. At some intermediate frequency, therefore, the reactive component of the impedance of the network must reach a maximum value, and at about this same frequency must produce its greatest phase-shifting effect by the local feedback. Similar remarks also apply to the inductance 11 at certain frequencies lower than that of anti-resonance. Although elements 11 and 12 may not be chosen independently if they are to anti-resonate at the wanted oscillation frequency, nevertheless they may be chosen together, so that the two frequencies of maximum phase shift, one higher and one lower than the operating value, are most effectively situated with respect to the critical frequency ranges which are represented in Fig. 3 by the passage of portions *ab'* and *ah'* near the point 1, 0. That is, the elements of the cathode network may be designed to give their maximum protection against undesired singing at or near the frequencies for which protection is needed. It should be obvious that this protection, as being with reference to frequencies outside the range of control by the feedback network 4, and therefore outside the locus 20 of Fig. 2 of applicant's previous patent, hereinbefore mentioned, cannot be secured by the degenerative action of said network 4 and therefore is impossible of accomplishment either in degree or in kind by the prototype circuit of said patent.

In concluding this specification it may be well to point out again that the large improvements over the prototype bridge oscillator which have been realized by means of the present invention have resulted partly from the physical benefits obtained by operating a mechanical resonator at extremely low amplitudes, and partly from increased amplification, which according to the bridge oscillator theory results in more sensitive stabilization, and which would be impracticable to utilize (owing to unavoidable phase shifts in the prototype oscillator) without the phase-correcting means disclosed herein.

While the invention has been described in connection with a particular embodiment, certain variations have been suggested and it is to be understood that many additional changes are possible within the scope of the invention, these changes in particular being directed to other forms of balanced feedback circuits.

What is claimed is:

1. In an oscillation generator comprising an amplifier and a feedback path coupling the output and input terminals thereof, a conjugate network included in said feedback path and connected at its conjugately related pairs of points, through the remaining portion of said feedback path if any, to said output and input terminals, respectively, said network including a frequency determining element and having a transmission characteristic providing a minimum feedback in regenerative phase substantially at the oscillation frequency and strong degenerative feedback frequencies removed therefrom, said frequency determining element comprising a mechanical vibratory means and the electrical elements of said network being so relatively dimensioned by assignment of radically different impedance values to certain functionally discrete portions thereof that said vibratory element tends to vibrate at a relatively low amplitude as measured by the condition of the rate of change of frequency with amplitude becoming a minimum.

2. An oscillation generator comprising an amplifier, input and output circuits therefor, and a Wheatstone bridge network conjugately coupling said input and output circuits, said network comprising a mechanical vibratory frequency determining element, the electrical dimensions of said network being such by radical disparity of impedance values in the network arms that said element tends to vibrate at an amplitude corresponding to a condition of the rate of change of frequency with amplitude becoming a minimum.

3. In an oscillation generator comprising an amplifier and a feedback path coupling the output and input terminals thereof, a conjugate network included in said feedback path connected at its conjugately related pairs of points, through the remaining part of said feedback path if any, to said output and input terminals, respectively and comprising a piezoelectric crystal element, said network having a transmission characteristic providing a minimum feedback in regenerative phase substantially at the oscillation frequency and strong degenerative feedback at frequencies removed therefrom, the electrical elements of said network also being so relatively electrically dimensioned by assignment of radically different impedance values to functionally discrete portions thereof as to provide a potential across said crystal element corresponding substantially to a condition of the rate of change of frequency with amplitude of vibration of said crystal as determined by said potential becoming a minimum.

4. An oscillation generator comprising an amplifier, input and output circuits therefor, and a Wheatstone bridge network conjugately coupling said input and output circuits, said bridge network comprising a piezoelectric crystal element, the relative electrical dimensions of said network by radical departure from uniformity of impedance values in the respective bridge arms and the electrical dimensions of said amplifier being such that said crystal element tends to vibrate at as small an amplitude as is consistent with the condition of a minimum rate of change of frequency with amplitude.

5. In an oscillation generator comprising an amplifier and a feedback path coupling the output and input terminals thereof, a conjugate network included in said feedback path connected at its conjugately related pairs of points, through the remaining part of said feedback path if any, to said output and input terminals, respectively and comprising a piezoelectric crystal element and a resistor the resistance of which is variable in magnitude with the strength of the current traversing it, said network providing a minimum feedback in regenerative phase substantially at the oscillation frequency and strong degenerative feedback at frequencies removed therefrom, the relative electrical dimensions of said network by assignment of radically different impedance values to functionally discrete impedance elements thereof being such that the energy dissipation in said crystal element is small as compared with that in said resistor, and the electrical dimensions of said amplifier in relation to those of said network being such as to maintain a desired degree of network balance.

6. The oscillation generator specified in claim 5 including additionally a negative feedback means associated with said amplifier and so electrically dimensioned as to insure that oscillation at any frequency other than that which is controlled and determined by the piezoelectric crystal element is effectively prevented.

7. The oscillation generator specified in claim 5, including additionally a negative feedback means comprising a circuit anti-resonant to the desired frequency in common to an input and an output path of the amplifier, whereby to introduce protective phase shifts for the avoidance of singing at extraneous frequencies induced by a high degree of amplification.

8. An oscillation generator comprising an amplifier, input and output circuits therefor, and a Wheatstone bridge network coupling said input and output circuits, the bridge comprising in one arm a piezoelectric crystal element, and in another arm a resistor whose resistance is thermally responsive to the current flowing therethrough, the remaining two arms having greatly different values of resistance whereby, for a near-balanced condition of the bridge, the energy dissipation in crystal element is small as compared with that in said resistor, an amplifier having as large a gain as may be necessary to compensate for the inefficient feedback to the input thereof, consequent on the resultant dissymmetry of the bridge, and a negative feedback means comprising a circuit anti-resonant at the desired frequency in a lead common to an input and an output circuit of the amplifier, for introducing protective phase shifts with respect to singing frequencies induced by the use of a larger amplifier gain than would be necessary with a more nearly symmetrical bridge which would result in turn from a normally increased amplitude of vibration of the crystal.

9. An oscillation generator comprising, an amplifier, a feedback path coupling the output and input terminals thereof, a frequency determining means being included in said feedback path, and, independently of said feedback path, a negative feedback means comprising a circuit anti-resonant to the desired oscillation frequency in common to an input and an output path of the amplifier, said anti-resonant circuit being so electrically dimensioned as to have a strong reactive feedback at one or more desired frequencies whereby to introduce protective phase shift for the avoidance of singing at said frequencies while the anti-resonant character of the circuit insures the lack of phase shift at said desired frequency.

10. An oscillation generator comprising, an amplifier, a feedback path coupling the output and input terminals thereof, a network being included in said feedback path and comprising a frequency determining means and a resistor the resistance of which is variable in magnitude with the strength of the current traversing it, said network providing a minimum feedback in regenerative phase substantially at the oscillation frequency and strong degenerative feedback at frequencies removed therefrom, and a negative feedback means associated with said amplifier and so electrically dimensioned as to insure that oscillation at any frequency other than that which is controlled and determined by the frequency determining element is effectively prevented.

11. The oscillation generator specified in claim 10 in which the frequency determining means is a piezoelectric crystal element.

12. The oscillation generator specified in claim 10 in which said negative feedback means comprises a circuit anti-resonant to the desired frequency in common to an input and an output path of the amplifier and so electrically dimensioned as to have a strong reactive feedback, with attendant phase shift, at one or more frequencies at which the oscillator tends to sing.

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