June 30, 1942. A. F. POMEROY 2,288,025

AUTOMATIC FREQUENCY CONTROL SYSTEM

Filed Aug. 3, 1940

FIG. 1

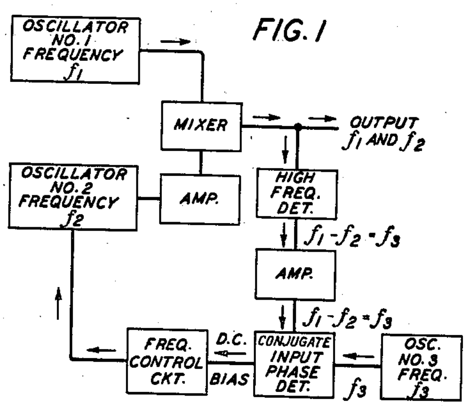


FIG. 2

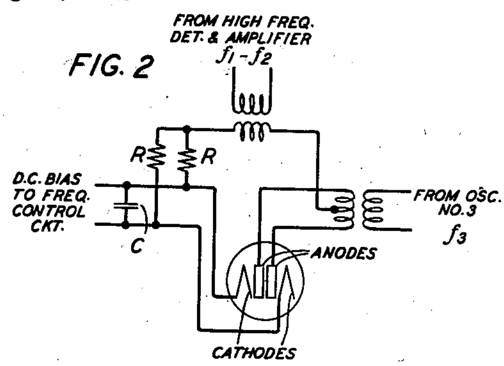


FIG. 3

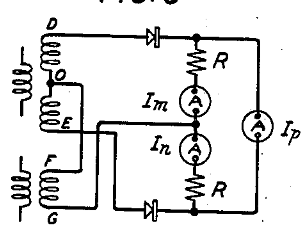


FIG. 4

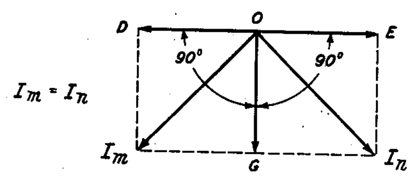


FIG. 5

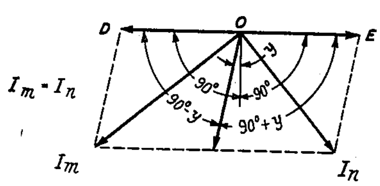


FIG. 6

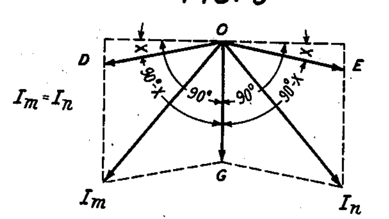
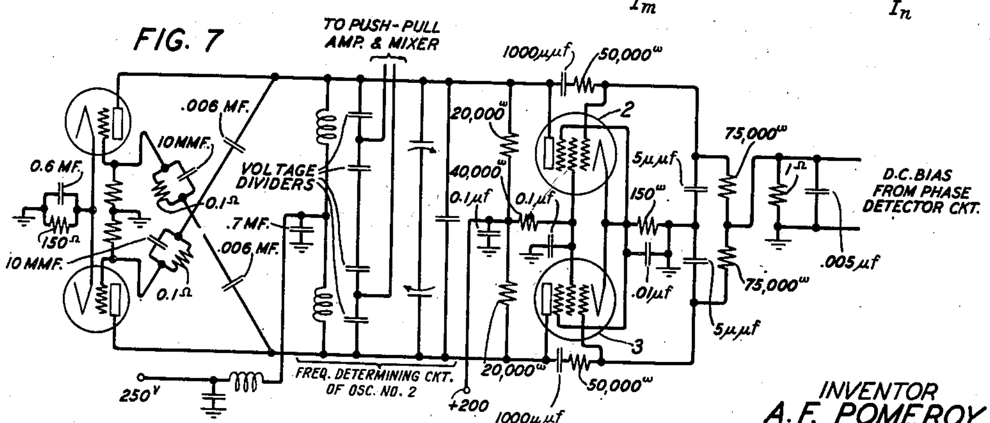


FIG. 7



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AUTOMATIC FREQUENCY CONTROL SYSTEM

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5 Claims. (Cl. 250—36)

This invention relates to automatic frequency control circuits and more particularly to such circuits as adapted to secure the frequency equality of two waves, the wave from the controlled source and the wave from the controlling source, to a degree measurable only in terms of phase difference. In a particular embodiment of the invention, the principle is used to maintain the difference between the frequencies of the waves from two oscillators equal to the frequency of a wave from a third, that is controlling, oscillator to the degree above indicated.

The principal object of the invention is to achieve the automatic frequency control of one oscillator by another oscillator to an extent not realizable by prior art means, and consistently with comparatively great simplicity of circuit and economy of plant.

A secondary object of the invention is to maintain with an extreme degree of fidelity the difference in frequency of the waves from two oscillators equal to the frequency of the wave from a third oscillator.

Having in mind the principal object of the invention, and especially the characteristically extremely close frequency correspondence of the two waves concerned, it is a subsidiary object of the invention to utilize in the operation of the control principle the phenomenon of an increasing phase difference which initiates a change of relative frequency. This principle, by inherency, tends to result in the maximum possible sensitivity and responsiveness of control. The means of the invention translates this relative phase change into a corresponding change of potential which is then used, through intermediary devices of the invention, to control the frequency of the controlled source.

As the invention is carried out in a preferred embodiment, the waves from the two sources concerned are impressed on a conjugate input phase detector, in the normal operation of which, that is, when there is exact correspondence between the waves from the two sources so that their frequencies and phases are both coincident, there is a balanced output potential with a resultant zero potential. A relative change of phase, however slight, which initiates a relative change of frequency is reflected in the creation of an unbalanced potential in the output circuit. This potential is caused to change the frequency of the controlled oscillator by acting on a reactance, or on reactances, in its frequency determining circuit. Since the effect, that is the control, is responsive to the initiation of the relative change in frequency and since this effect tends to change the frequency in such a direction as to tend to restore the equality relationship, the conditions are present for a continuous and extremely sensitive frequency control.

The frequency control by the unbalanced potential is achieved, in a preferred form of the invention, by the use of what has some times been denominated a reactance control tube principle wherein a change in control electrode potential of a reactance control tube effects a change in impedance of the control electrode-cathode circuit and, therefore, by the reflection principle in the impedance of the output circuit of the reactance control tube. In the instant case this output impedance change is a change in the inductance although the basic principle could be used to effect a capacitance change. This output circuit is caused to constitute, effectively, a part of the frequency determining circuit of the controlled source. By the use of a refinement of the reactance control tube principle, the single reactance control tube of the prior art is duplicated to constitute the reactance control tube circuit as a whole a push-pull combination of which would otherwise appear as conventional reactance tube used in a conventional way. This expedient is necessary if a push-pull oscillator is to be controlled by a balanced-to-ground reactance change. A push-pull oscillator is usually necessary in order to obtain high power output with low harmonic content.

The principle of the invention may be used alternatively, and as will be disclosed in the exemplification of the invention to be described in detail later, to maintain the difference in frequency of two unit oscillators exactly equal to the frequency of a third oscillator which may be thought of as the standard or controlling oscillator. In this instance the waves from the two unit oscillators are combined, as by an electronic modulator, and the resultant wave is used like the wave from the controlled oscillator in the generic case. The control over the frequency of this simulated generic controlled oscillator, and therefore, of the difference frequency in the output of the combining device, is best achieved by operating on one of the two unit oscillators, the variation of frequency of the wave therefrom, of course, being reflected in the difference frequency wave.

The control circuit of the invention as described immediately above has been used with success in envelope delay measurements as applied to circuits and apparatus for television transmission at frequencies ranging from 250 kilocycles to 5 megacycles with a difference frequency of 50 kilocycles. An envelope delay may be defined as the slope of a phase versus frequency curve and, therefore, is a measure of the retardation as indicated by loss of phase, of the very high frequency currents used in this art in its progress through the circuits and apparatus concerned. The choice of difference frequency was determined by the necessity of having the frequency interval Δf small enough so that the computed slope may be considered to be substantially the same as a differential of the phase with respect to frequency. This difference frequency had to be fixed to within at least two cycles per second, a standard difficult to be realized with other types of frequency control. It was found that the direct potential bias applied to the control electrodes of the reaction tubes, and resulting from the slight unbalance of the phase detector incidental to the operation of the circuit, was adequate to control the frequency extremely accurately over a wide enough range to cover the frequency drift of the oscillators. Since the two unit oscillators were of like type, the frequency drift tended to be in like directions so as to be mutually compensatory to a great extent.

At least two other applications of the frequency control circuit of the invention, especially in the form last described, readily present themselves, both applications involving the control of the oscillator frequency in demodulation. For instance in making phase delay measurements it is necessary to control rather closely the low frequency from the demodulator, this requiring a frequency control of the high order of merit represented by this invention. Likewise, in a wave analyzer the sensitivity may be increased as the width of the pass band in the low frequency system is decreased (this because of resistance noise) but such a narrow pass band requires extremely accurate frequency control in order that the beat frequency may stay in the band of the band-pass filter.

In the accompanying drawing:

Fig. 1 illustrates in highly diagrammatic form the relationship of the various units of the circuit of the invention as a whole;

Fig. 2 illustrates the conjugate input phase detector of the invention while Fig. 3 illustrates the same in a more diagrammatic form as an aid in the understanding of its mode of operation;

Figs. 4, 5 and 6 are electrical-geometrical-graphical devices which, taken together, illustrate the operation, under various conditions, of the phase detector of Figs. 2 and 3; and

Fig. 7 illustrates the frequency control circuit immediately posterior to the phase detector, or to an amplifier following the phase detector, together with the circuit of the unit oscillator directly controlled thereby.

The circuit of Fig. 1, disclosing in diagrammatic form the circuit or system of the invention as a whole in its embodiment in which the principle of the invention is utilized to maintain the difference in frequency of the waves of the two unit oscillators exactly equal to the frequency of the wave from a third, the controlling or standard oscillator, requires very little description supplemental to the description above in the statement of the invention, because of the functional labeling of the parts. It should again be emphasized that this circuit, while disclosing what is perhaps a preferred embodiment of the invention as expressed in a specific form, just as well discloses the generic form of the invention as directed to a means for maintaining an exact equality of two frequencies whether one of these two frequencies is a prime source or is itself a composite of two component frequencies, this as has been explained in the statement of invention above. In the detailed description to follow, in the interest of simplicity as well as clarity of disclosure, the functional labeling of the elements in the drawing will be used to identify these elements instead of perhaps the more usual device of literal or numerical labels.

The oscillators Nos. 1 and 2, generating waves of frequencies f_1 and f_2, respectively, should preferably be duplicates so that their normal frequency drifts are the same. These oscillators are connected, through the mixer, to the high frequency detector. An amplifier may be used between either oscillator, or each oscillator, and the mixer. It is shown used between oscillator No. 2 and said mixer. As illustrated the output of the oscillators either individually or together may be taken from the output of the mixer or, which is the same thing, from the input of the high frequency detector. Obviously the separate outputs from said oscillators may be taken directly from the oscillators, instead of through the intermediary of the mixer. The mixer is non-essential. It in no way compares in function with a modulator or detector circuit. As its name implies it is merely an effective means for mixing or arithmetically combining the waves from the unit oscillators and conditioning them for impression on the high frequency detector from which the difference frequency, as a modulation product, is derived. Practically, the mixer serves the function of predetermining the relative amplitudes of the waves so impressed on the high frequency detector and, therefore, commonly consists of a resistance network, the resistors of which match impedances and, as above, condition the impressed waves as to their relative amplitudes. It might well comprise, besides resistances, an electronic tube adapted to function as an amplifier but if so the amplifier must be distortionless. As above suggested, the mixer may be dispensed with, the relative amplitudes being determined by operation of the respective unit oscillators themselves.

Since the high frequency detector, by its modulation or demodulation action, gives a difference frequency f_1-f_2, this means that the frequencies of the unit oscillators are relatively high. In a sense, therefore, the combination of unit oscillators and high frequency detector as a means of obtaining a fairly small frequency, 50 kilocycles in a practical case, is an exemplification of the use of the heterodyne principle to easily and efficiently achieve a constant, but easily adjustable, low frequency by operation on one or other of said unit oscillators.

The amplifier disclosed as following the high frequency detector not only raises the difference frequency wave level but also tends to prevent reaction from oscillator No. 3, which is the controlling standard oscillator, on the high frequency detector output through the phase detector which is shown immediately following the amplifier. This phase detector is a means, somewhat analogous to a high frequency detector or demodulator for combining the difference frequency wave and the wave from the controlling oscillator, that is, oscillator No. 3. It differs in function from such conventional detector in that it is phase responsive so that the output product is expressed in terms of a difference in phase of the two conjugately impressed input waves. The sensitivity or responsiveness of the control is such that the two frequencies which are relatively controlled, that is, the difference frequency and the frequency f_3, are not only maintained so as to have like values, that is, so that there is a zero difference frequency, but that these frequencies differ by only a very small part of a cycle so as to be measurable, for practicable purposes, as a difference in phase rather than as an integral frequency difference. The control is exerted at the very beginning of a relative phase displacement which initiates relative change of frequency. Because the control is in this way effected so close to the fountainhead, the system of control is inherently more sensitive and responsive than by conventional methods of the prior art. This phase detector is disclosed in detail in Figs. 2 and 3 and its operation in Figs. 4 to 6 so that further description will be deferred at this time.

The output product of the phase detector is a direct potential the value of which is a function of the relative difference of phase so as to be directly responsive to the initiation of the relative frequency change. This potential is impressed on the frequency control circuit, which in turn is used to vary the frequency of one of the unit oscillators, oscillator No. 2 in the instant case. In the alternative instance of the use of a prime source as the controlled source, it would vary the frequency thereof. In either case the variation inherently tends to be in such a direction as to be compensatory, so as to tend to maintain the controlling and controlled frequencies in exact equality, that is, in locked synchronism. In the practical case there would be a slight phase difference between the waves, but the optimum condition in practice of a particular circuit of the invention has been that in which the two waves are maintained so closely in synchronism that there is only a small fraction of a cycle variation of this phase difference.

While various means have been suggested for achieving a frequency change by the use of a controlling direct potential, applicant suggests a modification of a principle of so doing involving the use of a so-called reactance control tube which makes use of the principle that a change of potential on a control grid is expressible as a change of shunt inductance of the output circuit. In the present case the output circuit is connected across the frequency determining circuit of oscillator No. 2 so as to effectively constitute a portion thereof, and, therefore, so that the variation of control electrode potential achieves a variation in frequency of the wave from said oscillator No. 2. By this electrical frequency control as distinguished from a conventional mechanical frequency control such as by variation of a variable inductance or capacity, a more sensitive and responsive control may be achieved, so as to more nearly realize the possibilities of the extreme sensitivity and responsiveness of the phase detector. The reactance control tube feature of this system differs from that of prior systems in that a parallel input arrangement of two reactance control tubes are used. These are necessary because a push-pull tube oscillator circuit is used. That is, it is necessary to change an unbalanced-to-ground direct potential to a balanced inductance change across the oscillator tubes. The continuity of the frequency control circuit, that is, the circuit utilizing the output of the detector to control the frequency of oscillator No. 2 will be described in greater detail in connection with Fig. 7.

The conjugate input phase detector disclosed in Fig. 2 is so functionally labeled as to fairly well indicate the continuity of the circuit and the function of the parts. The principle of its operation, as already described in the above treatment of Fig. 1 may well be exemplified by the use of a somewhat different continuity of circuit especially as to the tube element. In the form disclosed, the tube effectively comprises two rectifier paths each involving an individual anode and the nearest cathode. Because of the conjugate connection to the two anodes, as shown, of the circuits from the effective 50 kilocycle source, that is, from the high frequency detector and the standard or controlling frequency source generating a wave of the same frequency, the output potential, that is, the potential between the cathodes and across the bridge constituted by resistors R, will be a direct potential having a value determined by the phase relation of the input waves. When these waves have a quadrature relation, the resultant direct potential has zero value. If an initial condition is assumed where the phases have this relation (this, of course, also implying equal frequencies) any deviation therefrom, as representing an initiation of a relative change in frequency, would be reflected in the building up of a direct potential across this bridge. This potential is that used in the operation of the frequency control circuit of Fig. 7 whose operation has been described briefly in the description of that element in the over-all circuit of Fig. 1. The condenser C, the capacitance of which in a practical instance was .1 $\mu f.$, tends to short-circuit any alternating potential surviving from those impressed on the detector so as to better insure that the eventual output is a simple direct potential as is required for the effective operation of the subsequent frequency control circuit.

The operation of this phase detector is best explained by the use of the graphical devices of Figs. 4 to 6 taken with Fig. 3 disclosing the equivalent circuit of Fig. 2. The labeling of Fig. 3 is different from that of Fig. 2, except for the duplication of the labeling of resistors R, since the labeling of Fig. 3 has in mind the particular requirement of the graphical showings of Figs. 4 to 6. The labeling of the arrow pointed lines in said Figs. 4 to 6, which are somewhat analogous to vectors, indicate the potentials between correspondingly labeled points in Fig. 3. The correspondence of the respective elements of Figs. 2 and 3 should be quite evident. The transformers shown at the left, the secondary windings of which are indicated by DE and FG, respectively, are the two conjugate input transformers of Fig. 2, the two rectifiers, shown at the top and bottom, correspond to the rectifier or detector paths of the tube of Fig. 2 and the resistances R are the bridge resistances in Fig. 2 similarly labeled. The other elements of Fig. 3 are meters used in the operation of the circuit as will be evidenced from a description which follows.

This kind of conjugate input phase detector has the advantage of being able to indicate phase balance to as close as .01 degree and at the same time be independent of level changes in the two input potentials of about ±.5 decibel. In its operation let it first be assumed that the inputs to the two transformers have a quadrature phase relation, so that the phase of one potential differs from that of the other by 90 degrees. If the input transformer, whose divided secondary windings are coils OD and OE, is assumed to be perfect, the potentials across these secondary coils are in opposite phase and the conditions are as represented in Fig. 4. Let it be assumed that the rectifiers are such that the rectified output current depends only on the amplitudes of the respective input potential. In such a case the amplitude of the potential between points DG as applied to the upper rectifier will give a proportional current I_m through the upper resistor R. In Fig. 4 the line I_m is, therefore, shown in the direction the corresponding potential line would take if shown, and for simplicity its amplitude has been made to have the amplitude of that potential. Similarly, the amplitude of the current I_n resulting from the like potential as applied to the lower rectifier will be as indicated in Fig. 4. These currents I_m and I_n are the currents which set up the difference of potential across the output circuit of the phase detector. This is the potential which would exist across the condenser C of Fig. 2. In practice the conditions represented by Fig. 4 could easily be achieved by the use of a phase shifter of conventional type placed in the input circuit of either transformer. In this case the current in meter I_p would be the arithmetical difference of the two component currents I_m and I_n, this difference having zero value for the case assumed.

Now let it be assumed that the angular relationship of the impressed voltages, assumed in the treatment of Fig. 4 is changed by an amount y as shown in Fig. 5. The remaining part of said Fig. 5 shows the resultant condition. I_m no longer equals I_n and I_p is therefore no longer zero. It is to be noted that the rate of change of I_m-I_n is very rapid at the condition of balance so that a small phase departure produces a relatively large meter current. Therefore, the circuit constitutes a very sensitive phase detector. Fig. 6 shows that the same balanced conditions prevail even though the input transformer connected to oscillator No. **3** is not perfect so that the voltage OD is not exactly 180 degrees displaced from the voltage OE, in the case represented by Fig. 6 differing therefrom by $2x$ degrees. It is also evident that changes in amplitude of the input potentials do not affect the difference I_m-I_n for either of the conditions represented by Figs. 5 and 6 when the vector for the potential OG is symmetrically positioned with respect to the potentials OD and OE as would readily occur in practice. Instead of using the conjugate input transformers of Fig. 3 it is obvious that a Wheatstone bridge network comprised wholly of resistances could be used, the secondary windings of the input transformers being connected to different pairs of diagonally opposite points of the bridge. Such an arrangement might be of advantage since sometimes it is difficult to obtain coils having adequate midpoint balance.

Fig. 7 illustrates the frequency control circuit of Fig. 1 and its connection to the oscillator to be immediately controlled, that is, the oscillator No. **2**. Said oscillator may be any conventional type of push-pull oscillator, the push-pull type of oscillator being assumed in the instant case because of its relatively large power output with a comparatively low harmonic content. The use of the particular control circuit disclosed is necessary in view of this particular type of oscillator, for reasons that will be given later. In the interest of simplicity, the oscillator is shown without the elaborations which would distinguish a commercial circuit of the same type. In general, it is of the type of the push-pull oscillator of U. S. patent to Hartley 1,472,470, October 30, 1923. The frequency determining circuit so labeled, is related to the push-pull connected tubes in a now well-known manner. The important consideration is that the frequency determining circuit is connected to the output circuit of the frequency control circuit shown at the right. This frequency control circuit is a combination of tubes **2** and **3** and their immediately associated circuits in parallel input relationship. The continuity of the circuit is believed to be obvious without specific description of parts as identified by label. The electrical values disclosed are those for a typical circuit what has been found effective in practice.

The basic principle of operation of this circuit is that now quite commonly used for varying the tuning of a circuit by electrical, as distinguished from mechanical, means. The means involves the use of a reactance control tube, which means that a potential impressed on the control electrode of such tube determines to a great extent the input impedance of the said tube. Since said input potential, by reflection, effectively includes the impedance of the output circuit, or, from another point of view may be thought of as included therein, the ultimate result is that a tuned circuit connected to the output of the tube may be effectively adjusted in tuning by variation of the control electrode potential. The basic principle, as used in the synchronization control of an oscillator, and, therefore, somewhat analogously as in the present instance, is well illustrated by U. S. patent to Harper 2,066,528, January 5, 1937. Depending on the particular relation of electrical elements the output impedance change may be that of a capacitance or that of an inductance. In the instant case the change is an inductance change because of the circuits connecting the plates and control electrodes, although applicant's invention as pertaining to this reactance control tube circuit does not depend on the circuits individual to the respective tubes but to the push-pull relationship of such tubes. In order to control the push-pull oscillator assumed, by use of the reactance control tube principle, a balanced-to-ground reactance change is required. The parallel input control tube circuit converts an impressed unbalanced direct potential to such balanced-to-ground reactance change. The parallel input control circuit, therefore, adapts the operation of the control principle used to the conditions imposed by the choice of oscillator. The use of a single tube control circuit would result in a double ground on the oscillator circuit which would annul the effect of the control circuit and even the operation of the oscillator itself.

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 variations are possible within the scope of the invention, as defined in the appended claims.

What is claimed is:

1. A system for maintaining the frequencies of two waves in locked frequency relation, comprising a source of controlled frequency waves including a reactive frequency determining circuit, a source of controlling frequency waves, a conjugate input phase detector for combining the said waves with the resultant production of a direct potential varying as in accordance with the change in relative phase of the combined waves, and a reactance control tube circuit connecting said phase detector with said source of controlled waves for converting said changes in direct potential to corresponding changes in a reactance element of said frequency determining circuit, said source of controlled waves being a push-pull oscillator and said reactance control circuit comprising a pair of reactance control tubes in like parallel input relation, the output electrodes of said parallel input reactance tube circuit, between which the reactance change occurs, being connected to the frequency determining circuit of said push-pull oscillator so that its reactance is effectively a part thereof.

2. A system for maintaining the frequencies of two waves in locked frequency relation, comprising a source of controlled frequency waves including a reactive frequency determining circuit, a source of controlling frequency waves, a conjugate input phase detector for combining the said waves with the resultant production of a direct potential varying as in accordance with the change in relative phase of the combined waves, and a reactance control tube circuit connecting said phase detector with said source of controlled waves for converting said changes in direct potential to corresponding changes in a reactance element of said frequency determining circuit, said source of controlled waves being a push-pull oscillator in which the frequency determining circuit is connected between the output electrodes and said reactance control circuit comprising a pair of reactance control tubes in like parallel input relation, the output electrodes of said parallel input reactance control circuit, between which the reactance change occurs, being connected to said frequency determining circuit of said push-pull oscillator so that its reactance is effectively a part thereof.

3. A phase difference control system for controlling a given difference frequency wave as in accordance with the frequency of a controlling wave, comprising oscillators for generating two waves the difference between which is to be controlled, one of said oscillators comprising a reactive frequency determining circuit, a detector for combining the waves from said oscillator, a source of control waves, a conjugate input phase detector for combining the resultant difference frequency wave with the control wave whereby to obtain a direct potential variable responsively to changes in relative phase of the two waves impressed thereon, a reactance control tube circuit connected to said detector for converting said variable direct potential into a correspondingly variable inductance, and means connecting said control circuit with said frequency determining circuit whereby said variable reactance is effectively a part thereof, whereby the frequency of the oscillator comprising said frequency determining circuit may vary in frequency compensatorily and so as to maintain the difference frequency of which the frequency of its wave is a component in locked synchronism with the wave from the control oscillator.

4. The circuit specified in claim 3 in which the oscillator which comprises said frequency determining circuit is a push-pull oscillator and in which said reactance control tube circuit comprises a parallel input combination of two reactance control tubes, the output electrodes thereof, between which therefore the variable reactance occurs, being connected in symmetric relation to the frequency determining circuit of said push-pull oscillator.

5. The circuit specified in claim 3 in which the oscillator which comprises said frequency determining circuit is a push-pull oscillator having said frequency determining circuit connected across its output electrodes, and in which said reactance control tube circuit comprises a parallel input combination of two reactance control tubes, the output electrodes thereof, between which therefore the variable reactance occurs, being connected in symmetric relation to the frequency determining circuit of said push-pull oscillator.

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